Hazards presented by pyrolysis and combustion products during laboratory experiments and real incidents

by

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I declare that the material presented concerning work carried out in relation to the fire at the Lakanal block of flats on 3rd July 2009 is strictly limited to the work in BRE report number 259449 dated 17th December 2010, which was presented during the course of the inquest into the fire which took place between 14th January 2013 and 28th March 2013. There are pending legal proceedings in relation to this fire and as such this thesis is to be kept confidential for two years following submission.

This thesis has made use of a number of datasets and images from work carried out by the Fire Research Station or the Building Research Establishment (which subsumed the Fire Research Station in 1994).

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- Permission to use the material on the fire at Wealmoor Atherstone on 2nd November 2007 has been sought from Warwickshire Fire and Rescue Service; the client for the work, and BRE; the originator of the work. This includes Figure 140 to 179. The letter of permission from Warwickshire Fire and Rescue Service is provided at Appendix D. Permission from BRE for this material is included within the letter at Appendix A.

ABSTRACT

Heat, flame, smoke and fire gases are responsible for the vast majority of fire deaths and injuries and are all products of the chemical and physical processes that occur within fire. This is well known and supported by fire statistics but current fire safety does not directly consider these factors and the hazard they may pose to life. The aim of this thesis is to bring together knowledge from fire science with evidence from fire investigation to provide a way forward for improving fire safety and protecting life using sound scientific principles.

A number of major fires and the associated large scale fire reconstructions carried out as part of their investigation have been analysed to assess the way in which polymeric materials contribute towards the overall hazard and whether there are other factors tending to contribute to the hazard. The Stardust Disco fire highlighted the importance of lining materials in their contribution to both rapid fire development and toxicity. Maysfield Leisure Centre demonstrated the link between functional groups in polymers and the major toxicant likely to then contribute to the developing hazard. Harrow Court showed how a modern incident able to develop to flashover would produce a dramatic change in conditions, capable of overcoming fire fighters as well as civilians. Rosepark Care Home demonstrated the importance of simple fire safety measures such as the closing of doors in keeping products of combustion away from relevant persons. The Lakanal fire highlighted the potential complexity of these sorts of incidents and the way in which they tend to be the result of a large number of “things going wrong” all at once. The fire at Atherstone on Stour revealed the potential for rapid fire development to take place across very large environments, again sufficiently quickly to overcome attending fire fighters.

The work carried out has demonstrated the intrinsic link between the burning properties of materials with their toxicity, which are then further influenced by the way in which an environment can influence ventilation conditions, thermal insulation and pathways for fire to spread and impose hazards upon people in relevant areas. Fire safety has developed in such a way that flammability and toxicity no longer appear to be considered together, but the findings from the incident analyses indicate there appears to be a need to bring the subjects of toxicity and general fire safety back together.

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1. INTRODUCTION

The issue of the hazard presented to life by fire has been studied for as long as fire itself has been studied. The vast majority of deaths and injuries resulting from fires are attributed to exposure to heat and flame, exposure to smoke and fire gases, or a combination of the two. Heat, flame, smoke and fire gases are all products of the chemical and physical processes that occur within fire; however these processes are not directly considered or controlled within the modern fire safety framework.

The aim of this thesis is to bring together knowledge from fire science with evidence from fire investigation to provide a way forward for improving fire safety and protecting life using sound scientific principles. In order to achieve the aim, it was necessary to:

1. Examine the way in which the fields of fire safety, fire investigation have developed into their current form.
2. Consider the knowledge surrounding the fire performance of materials with respect to both flammability and toxicity.
3. Examine and consider the statistics that are available concerning fatal fires. Data was considered at both a national level, using publically available statistics, and at a local level, using data obtained from London Fire Brigade and its real fire library.
4. Investigate the link between fire hazard studied at bench scale level and full-scale fire incidents, to consider how an assessment of hazard (and therefore acceptability of hazard) is currently reached.
5. Investigate the way in which hazard to life escalates during the course of real incidents where multiple fatalities have occurred, so that the contributing factors to these escalations in hazard level could be identified and considered in relation to the assessment of hazard carried out at bench scale.

This was accomplished by investigating importance of fire toxicity and flammable materials with regards to cause of civilian deaths in fires; including the Stardust Disco, Maysfield Leisure Centre, Rosepark Care Home and Harrow Court fires, plus the more recent Lakanal fire. Fire fighter fatalities were studied as they provide a means of eliminating the issue of toxicity (through the wearing of breathing apparatus) so that the hazard arising solely from heat can be considered. This was done using the Harrow Court and Atherstone on Stour fires.

This thesis also looks at some aspects of analytical chemistry and computational fluid dynamics as part of computer fire modelling. These techniques are explained as they are relevant to some aspects of this work. However, it is not the intention of this thesis to provide a full review of the development and application of these techniques.

1.1. Fire Safety History

Fire safety is a discipline that has necessarily developed since man mastered the use of fire and other forms of energy harnessed since that time. As knowledge and understanding concerning fire and its interactions have developed, so have the methods to safeguard life from the effects of fire. Some of the earliest evidence regarding when man started using structured fire places and hearths to control the use of fire indicates that this occurred around 400,000 years ago.[1]

The issue of fire safety beginning to impact upon the design and construction of buildings is first recorded in the Annals of the History of Rome by Tacitus.[2] The great fire of Rome occurred in 64 AD. It was described as having started as a conflagration in an area of the city of Rome that was characterised by the *"inflammable wares"* contained in shops, the absence of any *"houses fenced in by solid masonry, or temples surrounded by walls, or any other obstacle to interpose delay"*.[2] Here the combined impact of building design and the contents placed into buildings by their occupants can be clearly seen. The fire went on to involve and destroy the entire city. On rebuilding the city, emperor Nero required *"The buildings themselves, to a certain height, were to be solidly constructed, without wooden beams, of stone from Gabii or Alba, that material being impervious to fire"*.[2]

The first recorded great fire of London occurred in 1135 AD when most of the city was built of wood; the houses were roofed with straw, reeds, and similar materials.[3] The London Ordinance of 1189 AD tried to limit the possibility of significant damage being inflicted upon the city as a result of fire; stone was made compulsory in the party-walls, but the rest of the buildings were made of anything, usually constructed of wood.[3] In 1212 a huge fire gutted a large area of

London and the death toll was said to be 12,000. This fire became known as the Great Fire of London (until four centuries later) and a further ordinance was issued.[3]

The need to limit fire was still known in 1598, where a survey of London stated *" … the houses in it were built all of wood, contrary to Richard I.'s edict that London houses should be built of stone, to prevent fire …"* and *"the houses in London were builded in stone for defence of fire … but of later time for the winning of ground taken downe, and houses of timber set up in place"*.[4] Ground was won (i.e. space saved) because it was easier to build timber houses tall: five storeys were not uncommon.

At the time of the Great Fire in 1666 buildings were mostly half timbered and pitch covered medieval buildings, mostly with thatched roofs.[5] Various laws had been enacted, obliging the parishes to provide buckets, ladders, squirts and fire hooks; but much of the equipment was rotten through neglect. Water supplies away from the banks of the river were scarce. As a result, once the fire started little could be done to stop its spread. Gunpowder was used to blow up buildings and try to create fire breaks to control the spread of the fire. Remarkably the Great Fire in 1666 resulted in only six confirmed recorded deaths.[5]

New London ordinances after 1666 (the London Building Act of 1667[6]) again tried to limit fire – by building with brick and stone and owners began to insure their properties against fire damage.[5] The new insurance companies, set up in 1668, realised that their losses could be minimised by employing men to put out fires. These led to the formation of the first fire brigades, albeit operated on a commercial rather than national basis[7]. Under this system, buildings displayed firemarks which identified which particular insurance company provided cover for the building. If a building were to catch fire several fire brigades would attend to see whether their mark was on the building. If no mark was displayed then the building would be left to burn. This system was considered successful at the time and continued until the 19th century.[8]

On 28th April and 24th June 1824, two disastrous and similar fires occurred in Edinburgh. The City Fathers considered that the fragmented cover provided by the fire insurance brigades contributed directly to the disorganised response to these fires and the scale of the damage caused by these fires. This led to the appointment of James Braidwood as Firemaster, or Master of Engines, in the first Municipal Fire Brigade in the British Isles; the Edinburgh Fire Establishment.[9] Braidwood later became the “Superintendent of the Firemen and Engines of the Phoenix and other co-operating Offices in London”.[9] There were 40 co-operating Offices in London alone funding this Brigade. The Brigade was later renamed as “The London Fire-Engine Establishment”.[8]

On Saturday 22nd June 1861, fire broke out in Tooley Street, London. The fire occurred where many warehouses stored goods including jute, hemp, cotton, spices, tea and coffee. The fire was able to spread quickly throughout the warehouses as many of the iron fire doors had been left open.[8] The fire resulted in the death of James Braidwood and the financial cost of this incident was so large that the insurance companies wrote to the Home Secretary stating that they could no longer be responsible for the safety of London and that this should be provided by a public authority. The Metropolitan Fire Brigade commenced on 1st January 1866 as a public service.[10]

In 1867 a Select Committee on Fire Protection was formed to *“inquire into the existing legislative provisions for the protection of life and property against fires in the United Kingdom, and as to the best means to be adopted for ascertaining the causes, and preventing the frequency of fires”*.[11] Similarly the Fire Offices' Committee (FOC) was established in 1868 by the major fire insurance companies.[12]

The following public bodies all contributed to the development of knowledge of fire safety in subsequent years and in conjunction with academia came to underpin the field of fire science that would develop around this time.

- The British Fire Protection Committee, 1895-1920
- The Royal Commission on Fire Brigades and Fire Prevention, 1923
- The British Standards Institute
    - Engineering Standards Committee, 1901-1918
    - British Engineering Standards Association, 1918-1931
    - British Standards Institute, 1931-present day (now a commercial body)

- International Standardisation Organisation, 1947-present day

In 1909 the FOC established a fire testing station in Manchester, the bulk of its work being devoted to improving the fire resistance of buildings for the insurers. In 1935 the UK Government Department of Scientific and Industrial Research (DSIR) and the FOC, along with other interested parties, opened a central Fire Testing Station in 1935.[13] In 1946, DSIR and the FOC established the Joint Fire Research Organisation to conduct research on all aspects of fire prevention and extinguishing. This became the Fire Research Board later that year, and in 1949 was renamed the Fire Research Station. In 1972 it joined two other research organisations (the Building Research Station and the Forest Products Research Laboratory) to form the Building Research Establishment (BRE), then part of the UK Government.[13]

It is important to recognise this history as it underpins today's modern fire safety framework and the way in which it is put together. Statutory fire safety is concerned solely with the protection of life and this is achieved through three major components in the current legislative framework; building design fire safety (currently under the Building Act 1984[14], Building Regulations 2010[15] and the Approved Documents), then what might be termed "occupant" or "content" fire safety (what people do with buildings after they are built) (currently under the Regulatory Reform (Fire Safety) Order 2005[16] and its supporting guidance documents), and finally through the provision for emergency response in the event of fire (currently under the Fire and Rescue Services Act 2004[17]). The other area of fire safety which has been mentioned in the history above is property protection. This is considered voluntary and is not directly covered in the first two components of Statutory fire safety, although Fire and Rescue Services are encouraged to protect property and the environment in the Act governing their work.

The way in which Statutory fire safety is made in the UK has changed in recent years. Whereas early attempts at regulating fire safety were prescriptive in their approach; requiring the use of non-combustible or limited combustibility materials for the construction of certain building features, or for Fire Brigades to have a certain number of fire stations and engines per unit area in their county, the legislative framework has now moved towards a fully performance based environment. The design and construction of buildings has to satisfy five key objectives; means of warning and escape, limiting internal fire spread, limiting concealed fire spread, limiting external fire spread and providing facilities for fire brigades, but whilst there is a suggested solution to the provision of these through the Approved Documents, building designers are free to adopt any approach that they see fit, provided they can justify it. Equally those responsible for the running of buildings have a duty to understand risks associated with their building and the activities going on within it, and to ensure an appropriate level of fire safety management is maintained, but there is no requirement to do so in a particular way (provided a record is kept). Fire and Rescue Services also have the freedom to fulfil their core duties (making provision for assisting with fire safety and making provision for fire fighting), but they may do so in any way they see fit through the current system of Integrated Risk Management Planning.

1.2. Fire Investigation

The relationship between fire safety and fire investigation is that of a feedback loop, presented in Figure 1. Fire investigation provides a means by which the efficacy of fire safety measures can be examined. It also provides an opportunity to assess whether there are any opportunities to improve those measures.

Figure 1 – The feedback loop of fire investigation, showing the role of incidents and the investigation of incidents in advancing knowledge and improving practice

Fire science very much underpins modern fire safety and fire investigation. Modern fire safety laws, codes and supporting guidance are almost universally developed in light of the latest knowledge that is available concerning fire science. It is a discipline that is still very much catching up with the developments made by its constituent scientific disciplines; principally physics, chemistry, biology and psychology. In spite of the on-going work advancing knowledge of the complexity of the combustion process, fire science continues to be dominated by the use of simple calculations derived from the empirical data. The standard texts used routinely throughout the industry[18,19], as well as the British Standards[20,21,22], are all based on empirical assumptions, and evaluate fire features such as temperature and flame length within the relatively broad concept of a room or compartment. These can be then used to provide accurate predictions of the outcomes from full-scale experiments such as fire reconstructions.

The first widely published material on the science of fire was Faraday's series of lectures on the chemistry of a candle 1861.[23] At this time the knowledge available from the fields of chemistry and physics were readily capable of explaining the basic phenomena responsible for the laminar flame of a candle. However, this scenario remains an area of research today despite the fact that its complexity pales in comparison to that of a compartment fire.[24]

Similarly fire investigators are expected to use the latest available information on fire science, albeit adapted through fire investigation textbooks, to understand and untangle the highly complex and inevitably highly damaged evidence that remains after a fire. The earliest known text aimed specifically at underpinning the field of fire investigation with the application of science was "Fire Investigation" by Paul Kirk, published in 1969.[25]

The primary function of fire investigation, in the majority of fires, is to identify where fires have started (the origin) and how they have started (the cause). Identifying the cause generally means identifying a fuel first ignited, an energy source capable of igniting that fuel, and the mechanism that has brought these two items together. Fire investigation has also increasingly examined the development of fire and how this has affected people, property and the environment.

Modern fire investigation is carried out by numerous different practitioners, both inside and outside of the criminal justice system. Fire and Rescue Service officers carry out fire investigation in support of the criminal justice system, to inform Coroners and for the completion of statistical returns to Government. Police officers tend only to get involved in fire investigation where there is a criminal aspect, although may also support Coroners' inquiries. Private investigators (including those based in academia) may be involved in fire investigation for any number of reasons; typically they are appointed by insurers or those involved in civil litigation but may also be appointed to assist Police or Fire and Rescue Services to assist with specialist aspects of their investigations.

BRE (originally as the Fire Research Station) provide comprehensive fire investigations in support of the Building Regulations (and its precursors and related legislation) on an ad hoc basis since 1948, and with a team of dedicated experts in this field since 1974. BRE has carried out fire investigations specifically to improve regulations for Government in connection with Building Regulations since 1988. The BRE fire investigation remit has been threefold; to examine fires:

- with implications for current regulations, codes and standards (successes and failures),
- of special interest to ministers or other officials,
- supported by research, which will bring a better understanding of hazards to humans and the environment.

1.2.1. **Fire Reconstructions**

Fire reconstructions are rare events as they require facilities of sufficient size to house them and, fortunately, the types of incident needed to justify them are infrequent. There are a few laboratories in the US of sufficient size to carry out full-scale fire reconstructions (including the Bureau of Alcohol Tobacco and Firearms' Fire Research Laboratory, Underwriters' Laboratories, and Factory Mutual's Fire Technology Laboratory), but most other countries possess no more than one such laboratory each.

Full-scale representations of scenarios under investigation are recognised by industry as being the best possible method of obtaining the relevant fire parameters and consequent toxicity of the conditions to which any potential victims are exposed.[26] In particular they allow investigators an opportunity to make use of knowledge around the development of a fire which has heretofore not been witnessed by anyone surviving the event. Fire reconstructions can aid investigators by providing information on one or all of the following:[27]

- How did items involved in the fire burn?
- How or why did the fire spread?
- How quickly did it spread?

- Did a particular material contribute?
- How hot did it get?
- How large in area did it get?
- How large did the heat release rate get?
- How smoky was it?
- How toxic was it?
- How did the building react during the fire?

Full-scale fire reconstructions also allow the establishment of timescales for an incident in a way which cannot be achieved with post incident scene examination and statistical analysis. As such it is possible to consider the rate at which conditions have deteriorated during the course of an incident for the victims of that incident and from that it may be possible to draw conclusions about potential ways in which the course of events might be altered by the introduction of changes to the conditions of that incident.

The fact that full-scale reconstructions tend to result from major catastrophes means that fire reconstructions have a strong record in using data from tragic events to inform the knowledge in fire safety and fire science. One example of this is the way in which experiments and reconstruction following the Woolworths fire in Manchester in 1979 led to both investigations into the fire behaviour of foam filled furniture and the potential benefits of sprinkler systems for commercial premises containing large unconfined fuel loads.[28]

1.2.2. **Computer Modelling**

Nowadays, computer modelling is sometimes used to support findings from the fire incident investigations. When used in conjunction with experimental work, computer modelling can be used to effectively extend the dataset, from the physical limits of the extent of a building that can be fitted inside a laboratory, up to the totality of the building.

Whilst it is not the objective of this thesis to provide full consideration to the use of computer modelling, some of the limitations of this discipline are introduced here. They are specifically related to the accuracy of computer modelling and the consequent limitations on the way in which computer modelling can be applied to fatal fires due to the requirements of the UK legal system (criminal, coroners and civil courts). A particular scenario has to be specified (room sizes, ventilation openings, fire location etc.) and then the simulation programs can make predictions of the impact of the fire on that scenario (temperatures, smoke concentrations etc.). For fire investigations, the results can then be compared with evidence from the fire to establish if the proposed scenario is consistent with the actual event.

There are a range of different simulation methods that can be used:

- "simple" calculations
- zone models
- computational fluid dynamics models (CFD models).

The "simple" calculations can be evaluated using a calculator or spreadsheet and are generally experimentally derived equations for features such as flame length. These are valid for conditions similar to the experiments used to develop them. The principal references for the calculations may be British Standards (such as Published Documents (PDs) from BS 7974 'Application of fire safety engineering principles to the design of buildings – Code of practice[20]), European and International Standards[29,30], text books[18,19] and peer reviewed journal articles[31].

Zone models exploit the typical development of a fire in a compartment to compute predictions of gas temperatures, layer depths, concentrations of gases etc. in a room or network of rooms with a prescribed fire and various ventilation conditions.[32] The main assumption is that, in each compartment, a smoke layer accumulates at the ceiling level. As the fire develops, the layer is filled by smoke and hot gases from the fire. Alternatively, smoke may enter through an opening (in a wall or floor) from another compartment, or smoke and hot gases may leave the compartment by an opening or by mechanical extraction. This basic principle is the basis for most design methods for smoke control in buildings. The computer software CFAST, developed by the National Institute of Standards and Technology (NIST) in the USA, is one of the most commonly used zone models, largely due to it being freely available online.[33] However, the zone approach will only give average values (e.g. of temperature) in each compartment and some of the processes in the model are only accurate over a limited range of conditions. To provide more detail and to ensure the key features of the movement of smoke and hot gases created by the fire are included, a more complex method is required.

Computational Fluid Dynamics (CFD) models are widely used to predict the movement of liquids and gases in various applications, for example weather forecasting and the design of aerodynamic surfaces for aircraft, cars and ships. CFD is also applied to fires to predict the movement of smoke and hot gases and is often used to demonstrate the capability of smoke control systems in buildings, car parks and other structures. It has also been used in fire investigation, notably the King's Cross enquiry where a CFD simulation identified a process that had not been considered during the investigation and was later shown, with reconstructions, to be a key feature of the fire: the discovery of the trench effect.[34,35,36] The CFD software package that has been used for fire modelling for both the Lakanal (section 3.1) and Atherstone (section 3.2) fires is JASMINE.[37,38,39]

The cost for the additional detail provided by a CFD model over a zone model is the computation time; a CFAST simulation may be run in a few minutes whereas a CFD simulation may take several days or weeks of computer time.

1.2.2.1. Accuracy

Unlike some applications of computer modelling, simulating real fires is not very precise and it is difficult to generate errors no greater than about 20%.[40] This is due to the large number of random factors that will occur, such as the composition and location of fuel items, moisture content, breaking of windows and the area of openings when pieces of glass fall out of a frame etc. These issues also apply to practical fire tests, such as reconstructions.

The combined use of computer modelling and experimental work is carried out in an attempt to minimise any such errors. Information is gathered from a number of sources; scene evidence, observations from the incident as well as work carried out experimentally and using computer modelling. This information is then brought together and cross-referenced as the work progresses in order to ensure that, as far as possible, the modelling that is carried out is representative of the physical phenomena that are responsible for the way in which the fire developed during the incident.

As such the application of computer modelling is most useful when it is used to visualise phenomena or generate data within a relatively confined space and/or time, the bounds of which can be effectively “defined” using other information (generally witness testimony and photographs) or data (from reconstructions, ad hoc experiments and test data).

There have been numerous cases where computer modelling has been presented in court, but a recent case resulted in it being thrown out due to doubts being raised about its accuracy, reliability and relevance.[41] This particular case involved the use of fire modelling to attempt to identify the area of origin and cause of a fire. Both of the reconstructions carried out by the author were supported by the use of computer modelling, and in both cases the computer modelling was submitted as evidence in court proceedings. However, in both cases computer modelling was used as a tool which had to be complemented and underpinned by other supporting evidence. Test data and reconstruction data have been used to validate the way in which the model simulates the combustion process and generation of heat and products of combustion. Evidence from the incidents have been used to provide a framework for the use of the computer model, such that the computer model is only used to fill gaps in information that are kept as small as possible. Throughout the process of computer modelling, engineering calculations are also used to ensure that the information gained from the computer modelling appears scientifically plausible when compared against more simplistic analysis, although experience and judgement on the part of the computer modeller and others involved in the investigation are also crucial.

1.3. Material Flammability, Toxicity and Fire Hazards

Once examination of the ignition of materials begins to consider the formation of flammable chemical species at the surface of the burning material, direct links can be drawn between burning behaviour and the formation of toxic species. Early work completed by Gann *et al.* considered the inter-relationship between burning rate (expressed as mass loss), toxicity of effluents and the impact of these two on overall fire hazard within an environment.[42]

The advent of modern plastics has meant that there has been a general move away from the use of natural materials towards synthetic materials. Without a full understanding of the way these products behave when exposed to fire, there is a risk that these will produce conditions that are more hazardous than was the case with natural materials. However, developing a complete understanding of this behaviour provides an opportunity to develop materials which are inherently less hazardous than the natural materials they replace.

Work carried out by Petajan noted that the addition of phosphate based fire retardants led to the production of a highly toxic substance: 4-ethyl-1-phospha-2,6,7-trioxabicyclo(2.2.2.)octane-1-oxide.[43] It also highlights the interaction between these two areas (fire flammability and toxicity). Further investigation by Wesolek and Kozlowski found that there was a balance to be drawn between the benefits of flame retardancy on ignition of fabrics versus the toxicity of effluents once these materials became involved.[44] This becomes really important with regards to the Furniture and Furnishings Regulations mentioned earlier, as the introduction of these regulations, whilst clearly having an overall benefit, may have resulted in an unintended consequence of increasing the toxicity of effluents once materials become involved in a fire and the severity of conditions within a fire compartment reach a point where they far outweigh the capacity of the fire retardant to limit burning rate.

Flammability of materials and toxicity of fire effluent must also be considered in relation to the stage at which a fire has reached. Fire stages are defined within BS ISO 19706[45], which outlines three principal stages of fire growth; non-flaming (stage 1), well-ventilated flaming (stage 2) and under-ventilated flaming (stage 3). Stage 1 is broken down into three sub-stages; self-sustaining smouldering, oxidative pyrolysis and anaerobic pyrolysis. Stage 3 is broken down into two sub-stages; a small localised fire in a poorly ventilated compartment and a post-flashover fire. Each of these stages/sub-stages is described by an expected surface heat flux, temperatures (fuel surface and upper compartment smoke layer), atmospheric oxygen concentration, equivalence ratio and relative quantities of effluent gases indicating completeness of combustion (given in terms of CO and CO_2).

Flammability of materials will contribute to the rate at which different fire stages are reached. The inter-relationship between flammability and the stage of a fire will then contribute to the burning rate of a material at any given time during the development of a fire. Burning rate, chemical composition and fire stage will then dictate the products of combustion which are formed and the quantities in which they are formed.

The standard tests which will be discussed in relation to both flammability and toxicity have necessarily been developed to provide reliable and reproducible means of assessing the performance of materials. The specific design of each standard test is based upon a particular situation that is intended to be reproduced to some extent to allow an assessment of performance in that situation to be made. However, the need for reproducibility and a pragmatic pass/fail criterion for use by designers, specifiers and regulators invariably necessitate the design of the standard test being abstracted to some extent from reality. As such, the appropriateness of a standard test versus an ad hoc experiment or a reconstruction when investigating an incident is subject to the question being asked. If the question is one of whether or not a material or design was compliant with legislation or a code, then the relevant standard test will be the appropriate tool to investigate performance. However, if one wishes to develop a fundamental understanding of the way in which a product material behaved during a real incident, then the conditions of that incident must be reproduced to the extent that the product or material is exposed to the same conditions as occurred during the incident.

1.3.1. **Flammability**

In the 1970s the increased manufacture and sale of plastics was beginning to have a tangible impact upon the fuel load present in fires in the UK and consequently the way in which these fires were developing. In particular, a concern was raised in the early 1970s regarding the use of expanded polystyrene tiles to line rooms and the impact this was seen to have had in the fires at the time.[11] Around the same time, another concern was expressed by the fire brigade on the changing nature of domestic fires, which were considered to develop more rapidly and create higher temperatures. It was assumed that this was being caused by the introduction of polymeric materials for furniture and furnishing.[11]

Following these concerns, an extensive programme of work was carried out by the UK Government to study the fire behaviour of materials used for furniture as well as to improve the test methods. Palmer *et al.* produced a series of recommendations for assessing the ignitability and the burning characteristics of polymeric materials.[46] This work ultimately led to the development of BS 5852 and the Furniture and Furnishings Regulations in 1988.[47,48]

1.3.1.1. Test Methods used for Flammability Measurements

There are numerous standard tests referenced in Approved Document B to the UK Building Regulations which deal with the flammability of a material or its surface.

For example, BS 476 Part 3[49] and Part 7[50] involve exposing a specimen to a radiant heat source and measuring the rate at which a flame propagates across its surface. BS 476 Part 4[51], Part 6[52] and Part 11[53] all involve exposing a sample to a heat source and/or furnace environment and measuring whether the specimen contributes to the temperature of the test environment. Both of the preceding sets of standard tests are beginning to be superseded by European and International test methods, with the long term objective of improving international harmonisation and therefore international trade of products. One such example of this is the suite of tests supporting BS EN 13501; the European method which corresponds to the system of categorisation in BS 476 Part 6 and Part 7, as well as many others. Parts 1 and 6 of BS EN 13501 are concerned with the reaction to fire properties of internal linings and so are relevant here.

It is worth noting that this particular suite of tests has allowed for a significant increase in the complexity of categorisation of products, as this scope for increased complexity might have implications for the development of future toxicity tests.

- BS EN 13501 Part 1 Fire classification of construction products and building elements. Classification using test data from reaction to fire tests,[54] and BS EN 13501 Part 6 Fire classification of construction products and building elements. Classification using data from reaction to fire tests on electric cables.[55] This standard brings together the tests listed below as a suite to determine the reaction to fire properties of materials and products, including propensity to burn, propagate flame spread, produce smoke and burning droplets. All of the test methods below represent some sort of well ventilated scenario, although this might reasonably be considered to be a worst case when measuring ignition/fire spread performance.
    - BS EN ISO 1182 Reaction to fire tests for products. Non-combustibility test.[56] This test is similar in methodology and scope to the BS 476 Part 4 and Part 11

tests and is intended to assess the contribution of a material or product to the temperature of a 750°C environment.

- BS EN ISO 1716 Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value).[57] This test is used to establish the absolute heat of combustion of a material or product. It is not intended to be representative of any realistic fire scenario.
- BS EN 13823 Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item.[58] The single burning item (SBI) test is intended to be a reproducible version of what is considered to be one of the more challenging or dangerous scenarios in fire; that of an item burning in the corner of a room. The material or product being tested is introduced as the surface lining of the two faces of the corner of the room and the response to the defined burning item is measured.
- BS EN ISO 11925 Part 2 Reaction to fire tests. Ignitability of building products subjected to direct impingement of flame. Single-flame source test.[59] This test exposes materials and products to a simple flame without any additional radiant heat exposure and as such can be considered to measure material and product performance against a simple pilot flame.
- BS EN ISO 9239 Part 1 Reaction to fire tests for floorings. Determination of the burning behaviour using a radiant heat source.[60] This test exposes floor coverings to a downward radiant heat source with pilot flame and allows measurement of wind-opposed flame spread across the sample. The method also provides the option of smoke opacity measurement.
- BS EN ISO 50399 Common test methods for cables under fire conditions – Heat release and smoke production measurement on cables during flame spread test – Test apparatus, procedures, results.[61] This test exposes vertical bundles of cable to a pilot flame and measures the consequent heat release rate, smoke production rate (measures via optical extinction) and production of any flaming droplets or particles.
- BS EN 60332 Part 1-2 Tests on electric and optical fibre cables under fire conditions – Test for vertical flame propagation for a single insulated wire or cable – procedure for 1 kW pre-mixed flame.[62] This test exposes cables to a

simple flame without any additional radiant heat exposure and may be considered analogous to BS EN ISO 11925 Part 2, albeit designed for cables.

The aforementioned tests have been arranged into **Table 1** below, where it can be seen that, across the various types of product that this suite of tests can be applied, there is a general trend in severity of conditions to which samples are exposed, ranging from a simple flame test for lower classes, through more pragmatic and situation specific tests, up to the most severe tests imposing furnace conditions to force combustion or measure calorific contribution to a fully developed, potentially post-flashover, fire.

	Product type			
Class	General construction products	Floorings	Linear pipe insulation	Cables
A1	EN ISO 1182 Non-combustibility EN ISO 1716 Heat of combustion	EN ISO 1182 Non-combustibility EN ISO 1716 Heat of combustion	EN ISO 1182 Non-combustibility EN ISO 1716 Heat of combustion	EN ISO 1716 Heat of combustion
A2	EN ISO 1182 Non-combustibility EN ISO 1716 Heat of combustion EN 13823 Single Burning Item	EN ISO 1182 Non-combustibility EN ISO 1716 Heat of combustion EN ISO 9239-1 Radiant panel test	EN ISO 1182 Non-combustibility EN ISO 1716 Heat of combustion EN 13823 Single Burning Item	EN 50399 Flame spread, HRR EN 60332-1-2 Wire vertical flame
B	EN 13823 Single Burning Item EN ISO 11925-2 Small flame test	EN ISO 9239-1 Radiant panel test EN ISO 11925-2 Small flame test	EN 13823 Single Burning Item EN ISO 11925-2 Small flame test	EN 50399 Flame spread, HRR EN 60332-1-2 Wire vertical flame
C	EN 13823 Single Burning Item EN ISO 11925-2 Small flame test	EN ISO 9239-1 Radiant panel test EN ISO 11925-2 Small flame test	EN 13823 Single Burning Item EN ISO 11925-2 Small flame test	EN 50399 Flame spread, HRR EN 60332-1-2 Wire vertical flame

D	EN 13823 Single Burning Item EN ISO 11925-2 Small flame test	EN ISO 9239-1 Radiant panel test EN ISO 11925-2 Small flame test	EN 13823 Single Burning Item EN ISO 11925-2 Small flame test	EN 50399 Flame spread, HRR EN 60332-1-2 Wire vertical flame
E	EN ISO 11925-2 Small flame test	EN ISO 11925-2 Small flame test	EN ISO 11925-2 Small flame test	EN 60332-1-2 Wire vertical flame
F	No performance determined	No performance determined	No performance determined	No performance determined

Table 1 – Test methods needed to establish Euroclasses of products under BS EN 13501

European standards and tests have developed apace since the founding of CEN (European Committee for Standardisation) in 1961. European tests have been developed to promote harmonisation of standards and interoperability of products throughout Europe, with the ultimate objective of strengthening the European economy within the global marketplace. However, the development of European standards and their imposition on individual countries through European Directives is sometimes at odds with the individual needs of those countries such as the UK. Additionally, as in the example above, the development of European standards provides the possibility for the complexity of test methods and systems of categorisation to increase, which can be viewed as an opportunity or a hindrance for individual member states, depending upon their individual requirements. Consequently the UK continues to maintain its own British Standards, whether or not their scope has been addressed by an equivalent European standard.

The cone calorimeter; BS 476 Part 15 and ISO 5660 Part 1[63], incorporates some aspects of both of the groups of test methods outlined above; variable incident radiant heat can impact upon the burning behaviour of the sample, which is then measured and can be used to assess contribution to overall fire size. This test method produces quantitative data which is useful for quantitative hazard analysis, but is seldom used, and not part of UK building regulations.

1.3.2. **Fire Toxicity**

The concept of smoke posing toxic hazard was recognised long before any specific research was carried out.[64] In 1893, the Lancet published articles showing the importance of optimising the combustion process in cooking and heating appliances to avoid potential negative effects on the health.

As mentioned earlier, the British Fire Protection Committee was one of the first public bodies set up to look into the effects of fire and potential hazards coming from them. It is interesting to note that, during 25 years of operation (1895-1920) and the production of 251 “Red Books” (the name given to the series of publications produced by BFPC), no single publication ever dealt specifically with the issue of smoke production during fire or the effect of smoke on people.[65,66]

The Cleveland Clinic fire of 1929 is reported to be the first incident to lead to significant work in the field of fire toxicity.[67,68] During the incident, the production of toxic gases from nitrocellulose X-Ray films is believed to have caused the deaths of 125 individuals. Investigative work was carried out to examine the gases produced during the incident and implications with regard to the cause of death. The three principle gases that were identified during this work were carbon monoxide, nitrous fumes (nitrogen oxides) and hydrocyanic acid (hydrogen cyanide).[69] Further work in the United States led to the publication of the first book considering the cumulative effects of individual gas species on the overall toxicity of an atmosphere.[70]

In the UK, two schools of thought (and corresponding areas of research) appear to have been emerging in the 1950s, one devoted to the understanding of the diversity of chemical species that can be produced by the combustion process (linked directly to the earlier work in the USA)[71,72], whilst the other simply considering smoke to pose a general toxic hazard; the greater concern being means of maintaining separation between building occupants and the toxic smoke[73,74], generally through provision of adequate means of escape. The latter of these two groups had greater success with influencing the first UK Building Regulations and the subsequent, up until the now current supporting Approved Documents.[75,76]

Work published during the 1960s focussed on the rapid introduction of plastic materials into buildings (see chapter 1.4).[77,78,79] The focus of UK Government research (unpublished at that time) shifted to start taking account of the range of ventilation conditions under which combustion products may be produced and therefore the effect of ventilation on the toxic potency of smoke. Some work was carried out on room scale experiments, however the majority of work focussed on the bench scale.[80,81,82,83,84,85]

Work published in the 1970s comprised the initial work developing an overview of the fire toxicity problem and some detailed assessment of the toxicological impact of smoke. Woolley and Fardell submitted a paper to the first issue of Fire Research (named the Fire Safety Journal thereafter) where they set out the fundamental relationship between elements and functional groups present within polymeric materials, and the products of combustion likely to evolve and impact upon the safety of people in the vicinity.[86] Complementary work was then also presented by Einhorn and Grunnet regarding the toxicological effects of combustion products.[68] Even at this relatively early stage in developing the knowledge in this area, focus was already upon the formation of carbon monoxide and hydrogen cyanide and their impact upon overall toxicity and some simple consideration of decomposition routes.[87,88] The focus of UK Government research (unpublished at that time) was on the use of gas chromatography coupled to mass spectrometry.[89,90,91]

During the 1980s work began improving on the level of detail to which it was possible to understand the reaction mechanisms responsible for the formation of toxic species.[92] Toxicity assessment was still largely based upon exposure of animals to fire effluent and methods were being investigated to refine this approach, but work was also being carried out to examine the chemical species responsible for the toxic effect of smoke, still largely focussed on carbon monoxide and hydrogen cyanide.[93,94,95,96]

The most significant work in the field of fire toxicity was completed during the 1990s. Studies and discussions at the time attempted to collate and consider all of the information that had been generated in the past.[97,98] Work began to consider the equivalence ratio concept and the stages during a fire and how these stages might affect burning conditions.[99]

One paper by Clarke and Hoover considered the need for a rigid method to establish pass/fail criteria for the toxicity assessment.[100] However, they also pointed out difficulties of toxicity analysis due to dependence on many different variables. This was also recognised by Babrauskas, who carried out extensive work investigating the relationship between bench and full-scale data.[101,102] Babrauskas acknowledged that there was a need for some form of ranking system for products, but that these ranking systems presented no prospect of any quantitative assessment of risk.[103] As such the test methods for ranking products and those for producing quantitative data appeared at this time to be mutually exclusive.

During the 1990s the growing popularity of fire safety engineering and performance based design meant that there would be an increased demand for establishing a reliable quantitative method for the toxicity assessment. The development of the steady state tube furnace by Purser *et al.* in 1994 became a significant step in assisting with this approach (see "Fire Testing") and it would also begin to bring the issue of fire toxicity closer to the issue of flammability and burning conditions.[104]

Throughout the early development of fire toxicity research, identification and quantification of toxic species produced in different test methods had been developed. The most common were either, using reagents and solvents to extract toxic species so that they could be analysed by chromatographic techniques (gas, liquid or ion) or simply by colorimetric gas detector tubes (Draeger tubes). More recently industry has been seeking to eliminate these techniques replacing them by Fourier Transform Infrared Spectroscopy (FTIR), due to its capability for continuous analysis of fire effluents during both standard and large scale experiments.[105] FTIR has been developed as a means of quantifying the concentrations of known chemical species on-line, however, the data produced by this technique does not favour novel analysis. Both quantification and identification of species is highly reliant on either an operator or software being capable of separating out the overlapping of peaks from the various chemical species that might be present in the fire effluent.[106,107] In the case of software identification, this means having a suitable library of spectra of previously known species.

The specific chemical species responsible for the overall toxic (including irritancy) hazard in fires are too numerous to list; indeed the sheer number of products of complete and incomplete combustion that may be produced from any one fuel has yet to be fully established. There are, however, eight compounds known to make a significant contribution to toxicity, either by contributing directly to asphyxia or by contributing to incapacitation due to irritant effects, identified in ISO 13571 and ISO 13344.[108,109]

Asphyxia arises chiefly from exposure to carbon monoxide and hydrogen cyanide as well as lack of oxygen (exposure to an oxygen depleted atmosphere). The common aspect of the mechanisms of death by asphyxia is the deprivation of oxygen to cells in the body. Carbon monoxide binds with haemoglobin in the blood, preventing transport of oxygen from the lungs to other tissues in the body. Hydrogen cyanide interferes with the chemical processes in cell mitochondria (which are responsible for the reaction of metabolic sugars and oxygen to release carbon dioxide, water and energy).[110] The impact of asphyxiant gases on the body is directly proportional to respiration rate, so carbon dioxide also contributes to asphyxia, but only due to its presence in elevated concentrations increasing respiration rate.[111]

Identifying the significance of asphyxiant gases postmortem is done through quantification of species present in blood. Carbon monoxide is quantifed via the proportion of haemoglobin to which it has bound to form carboxyhaemoglobin (COHb). Modern figures provided in the SFPE Handbook indicate that 50-70% COHb in the blood is a good indicator that carbon monoxide has caused death. However these figures can be lower depending upon the health and physiology of the subject. Similarly, 40% COHb is expected to result in unconsciousness in an adult but this may be lower (~30%) if there are other health factors, particularly any cardiovascular factors. Exposure to hydrogen cyanide is established through quantification of the cyanide ion (CN^-) in the blood. Concentrations of 2.0 to 2.5 μg CN/ml will likely result in incapacitation (unconsciousness) whereas concentrations of 3 μg CN/ml and above will be sufficient to cause death. However, quantification of hydrogen cyanide exposure is complicated due to it not remaining persistent in the blood. Cyanide concentration is likely to drop by as much as 50% during the first 1-2 days after death so it is important to obtain and analyse samples as quickly as possible after death in order to obtain reliable data.[111]

The chemical species giving rise to irritant effects which are commonly considered are the halogenated acid gases (hydrogen chloride, hydrogen bromide and hydrogen fluoride), nitrogen oxides (nitric oxide and nitrogen dioxide), sulphur dioxide, acrolein and formaldehyde. The principal impacts of irritant gases are twofold; from relatively low concentrations they give rise to sensory irritation (pain to and watering of the eyes, excessive coughing and mucus production); at higher concentrations they can lead to chemical burns, which are particularly significant in the respiratory tract. Sensory irritation may not be dangerous in itself, but can impede escape, thereby increasing the dose of asphyxiant gases to which a person attempting to escape a fire is exposed. Where damage to the respiratory tract does occur, this can be fatal, although death can be delayed some hours after exposure has ceased.

1.3.2.1. Test Methods used for Fire Effluent Measurements

Neither the current 2013 version of Approved Document B nor any previous version has yet made any mention of a toxicity test.

Given the complexity of fire toxicity, it may be considered somewhat unsurprising that there are competing approaches to its assessment by standard test method. As previously mentioned, test methods can be developed to attempt to replicate some aspect of a real fire scenario or can be developed purely to provide a means of ranking products with a pass/fail criterion or single quantifiable parameter. The need for a means to rank products has meant that test methods are in use that do not necessarily reflect any of the ISO fire stages particularly well. Each of the competing approaches have support from different parts of the fire sector, with simplistic test methods suited to the creation of an easy-to-use ranking system being favoured by product manufacturers and specifiers, whilst more complex tests, usually more suited to replicating one or more fire stages accurately tends to be favoured by researchers and academia. The two principal methodologies which are being debated currently are the tube furnace and the smoke box methodologies, although each of these are actually sets of methodologies within which there is further wide variation and competition between methodologies.[112]

- Open tests

Open tests such as the cone calorimeter can only replicate well ventilated conditions. The cone calorimeter itself was not developed to assess toxicity but rather flammability (see 1.3.1.1), although it can be adapted to allow measurement of species in addition to its intended O_2, CO and CO_2 measurements.

- Closed smoke chamber test methods

There are numerous test methods based around the concept of a closed chamber in which a sample is burnt so that effluents can accumulate for sampling and quantification. In the UK, the most well-known of these is the BS EN ISO 5659 smoke box, although there are a large number of closed smoke chamber tests developed and in use across the world.[113,114]

The ISO 5659 test method describes a smoke chamber within which fire effluents are generated using a cone heater arrangement above a horizontal specimen (similar to the cone calorimeter). The method is not directly aimed at toxicity assessment but has long been adapted to allow sampling of fire effluents; either from the hot smoke layer that forms in the box or from the entire volume after mixing has been forced, normally via the use of a fan. The method results in ventilation conditions changing as the test progresses, due to the finite amount of oxygen in the box being used up and replaced by the products of combustion from the burning sample.

- Flow through methods (non-steady state)

Flow through methods all involve passing an air supply (or other controlled atmosphere) over a sample. There are a number of methods and the principal variables which distinguish them are the air flow, mass and shape of sample and the temperature of the combustion zone. The most common of the flow through methods is the static tube furnace method which involves placing a sample inside a tubular furnace (at a fixed temperature) through which air is passed from one end and the effluents collected from the far end. It tends to be used for electrotechnical products, but has also been used for other applications like materials to be used as compartment linings in railway rolling stock.[115,116]

- Steady state flow through methods

Steady state methods seek to control the ventilation and fuel delivery rates and to control the burning rate by introducing the fuel/air mix into a combustion chamber with a temperature gradient. There are a number of national methods and an international method; the ISO 19700 steady state tube furnace or Purser furnace.[117,118] The steady state tube furnace is a method of controlling the ventilation, temperature and rate of combustion of a material so that toxicity data can be collected for all of the relevant fire stages when a material may burn and contribute to the overall toxicity of a fire situation.

It is reasonably well known amongst those studying the toxicity of fire effluents that the composition and therefore properties (including toxicity) of combustion products varies with respect to ventilation conditions.[119] It is generally well accepted that volatiles will differ between decomposition atmospheres like air or nitrogen or under different thermal conditions. At present, the issue of ventilation effects on combustion effects tends to be dealt with by using the concept of equivalence ratios which is used to describe the ratio of fuel to air with respect to the stoichiometric fuel:air ratio. The steady state tube furnace, or Purser furnace has clearly demonstrated that the burning conditions have a direct impact upon the formation of toxic combustion products and that although flammability and toxicity have been considered in relative isolation over a number of years, they actually need to be considered together when attempting any assessment of the overall hazard to life posed by fire.[111,112]

- Full-scale room tests

There are a small number of standard tests which are carried out at full room scale. The ISO 9705 room corner test is designed to consider the whole room impact that a surface lining material may have.[120] The method allows for assessment of both flammability (heat release rate, heat flux and temperatures) and toxicity. The method is, however, limited by the size of the 9705 room and its insulation properties, although fire engineering calculations may permit adaption of data from this test to other scenarios.

The aforementioned types of toxicity test have all been compared and/or validated against full-scale data.[112] The comparisons have shown that there is variability between test methods in terms of the comparability of equivalence ratio within the test with global equivalence ratio of a large-scale fire. However, as mentioned above, the different test methods are suited to replicating different fire stages and the generation of toxic effluents arising from these.

1.3.3. **Tenability Limits**

There are two international standards used for calculating the tenability of atmospheres in which mixtures of fire effluents are present; ISO 13571 and BS ISO 13344.[108,109] Both of these standards propose additive approaches to calculating overall toxicity, with an increase in uptake associated with elevated carbon dioxide concentrations (although the increased uptake is dealt with differently in the two standards). ISO 13571 uses data derived from experiments with primates whereas BS ISO 13344 uses data from experiments with rats and provides a bioassay method for both confirmation of results and generation of toxicity data for effluents not covered in the standard. The method of ISO 13571 has been used for this work, which provides a number of equations for the quantification of hazard to life (dealt with as Fractional Effective Dose). The basic form of the equation for calculation of total FED (Fractional Effective Dose – where dose is the product of quantity and time) based upon specific exposure dose of each component which would result in incapacitation and death is:

$$FED = \Delta t \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(Ct)_i} \Delta t \qquad (1)$$

Where

C_i is the average concentration of asphyxiant gas (ppm)

Δt is the time increment (minutes)

$(Ct)_i$ is the specific exposure dose that would cause incapacitation or death (ppm·minutes)

Asphyxia due to carbon monoxide is calculated using an expanded form of equation 1:

$$FED = \sum_{t_1}^{t_2} \frac{\varphi_{CO}}{35000} \Delta t \qquad (2)$$

Where

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

Δt is the time increment (minutes)

Asphyxia due to hydrogen cyanide is also calculated using an expanded form of equation 1:

$$FED = \sum_{t_1}^{t_2} \frac{\exp(\varphi_{HCN}/43)}{220} \Delta t \qquad (3)$$

Where

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

Δt is the time increment (minutes)

Both equations 2 and 3 must be used in conjunction with the following equation, which presents the increased uptake of asphyxiant gases due to the increase in respiration rate caused by elevated concentrations of carbon dioxide:

$$v_{co_2} = \exp\left(\frac{\varphi_{CO_2}}{5}\right) \quad (4)$$

Where

v_{CO2} is the frequency factor due to carbon dioxide

φ_{CO2} is the average concentration of carbon dioxide (percent by volume)

Incapacitation due to irritant gases is calculated from equation 5. Note that incapacitation due to irritant gases is dependent upon instantaneous concentration and not a cumulative dose, so there is no summation or time component to the calculation.

$$FEC = \frac{\varphi_{HCl}}{F_{HCl}} + \frac{\varphi_{HBr}}{F_{HBr}} + \frac{\varphi_{HF}}{F_{HF}} + \frac{\varphi_{SO_2}}{F_{SO_2}} + \frac{\varphi_{NO_2}}{F_{NO_2}} + \frac{\varphi_{acrolein}}{F_{acrolein}} + \frac{\varphi_{formaldehyde}}{F_{formaldehyde}} \quad (5)$$

Where

φ_n is the average concentration of n irritant gas (ppm)

The values given in ISO 13571 for incapacitation due to irritancy can be entered into equation 5 as follows:

$$FEC = \frac{\varphi_{HCl}}{1000} + \frac{\varphi_{HBr}}{1000} + \frac{\varphi_{HF}}{500} + \frac{\varphi_{SO_2}}{150} + \frac{\varphi_{NO_2}}{250} + \frac{\varphi_{acrolein}}{30} + \frac{\varphi_{formaldehyde}}{250} \quad (6)$$

The hazard arising due to exposure to heat can be calculated in one of three ways. The effect of exposure of skin to radiant heat is calculated by:

$$t_{Irad} = 4q^{-1.35} \quad (7)$$

Where

t_{Irad} is the time to burning of skin (minutes)

q is the radiant heat flux (kW/m^2)

The effect of hyperthermia due to convected heat for fully clothed subjects is calculated by:

$$t_{Iconv} = (4.1 \times 10^8)T^{-3.61} \quad (8)$$

Where

t_{Iconv} is the time to incapacitation due to hyperthermia (minutes)

T is the temperature (degrees Celsius)

The effect of hyperthermia due to convected heat for unclothed or lightly clothed subjects is calculated by:

$$t_{Iconv} = (5 \times 10^7)T^{-3.4} \quad (9)$$

Where

t_{Iconv} is the time to incapacitation due to hyperthermia (minutes)

T is the temperature (degrees Celsius)

The initial development of the concept of FED was carried out by Hartzell et al.[121] The relationships described above were and are based upon EC_{50} values for each of the species considered (Effective Concentration resulting in death or incapacitation of 50% of subjects following a given exposure time). As such, an FED of 1 indicates that the cumulative effect of the gases considered is expected to result in death or incapacitation of 50% of those people exposed to those conditions. However, different species have different dose-effect relationships and so values above 1 cannot be considered representative of the way in which the hazard rises above that point. However the numerical relationship between FED and species concentration is largely a direct one (except where significant CO_2 concentrations cause increased uptake). During the reviews carried out later, FED plots are shown up to a maximum value of 5 so that the reader may see the rate at which conditions are worsening shortly beyond time of death.

1.4. Fire Statistics

Statistics on fires in the UK have been collected formally since the 1940s. Numbers of fatalities across the UK are available since 1950. The detail of the data contained within the UK fire statistics has varied widely over the years; there have been numerous formats of data collection form, including the K433 fire report form, FDR1 (Fire Damage Report) form and the most recent electronic IRS (Incident Recording System) form. During the various revisions to the collection of UK fire statistics, there have been changes to the structure of the forms and also to the categorisation of fires and wording describing these categories. More recent changes in the structure of the UK Government have led to collection of statistics taking place at devolved level, with statistics for England, Wales, Scotland and Northern Ireland all being collected and analysed separately. All of these changes necessarily mean that caution must be applied when comparing datasets that have been collected over a number of years, although the use of statistics remains one of the most powerful tools available for assessing trends in the incidence of fires in the UK and for identifying areas for further work.

Two principle levels of data will be analysed in this chapter. Given the subject of this thesis, the area of interest is that of the chemical mechanism which is responsible for death in fatal fires; identified through deaths caused by heat and flames versus deaths caused by inhalation of smoke and toxic gases. During the early years of fire statistics being collected, the data on cause of death was supplemented by information on the fuels involved in the fire and the location of the victims in relation to the origin of the fire. This level of detail is no longer available in national statistics, but is still collected by London Fire Brigade. Data was requested and gratefully received from London Fire Brigade for 1st April 2009 to 31st March 2012. It has been assumed that data from London is directly comparable to data at a national level.

1.4.1. **National Fire Deaths Data**

The general trend in fire deaths for the UK is shown in Figure 2, where it can be seen that there was a general increase in the number of fire deaths from 1950 to 1980, with a subsequent and consistent decline in numbers until the present day. Note that, as previously mentioned, statistics are no longer gathered in a way that allows direct comparison with historic data; devolution of governments in the UK means that England, Wales, Scotland and Northern Ireland now all collect their own data individually and it is not available as a complete set. In addition, at the time of writing, the devolved departments have not completed their own analysis so only provisional data at regional level is available, therefore has not been used.

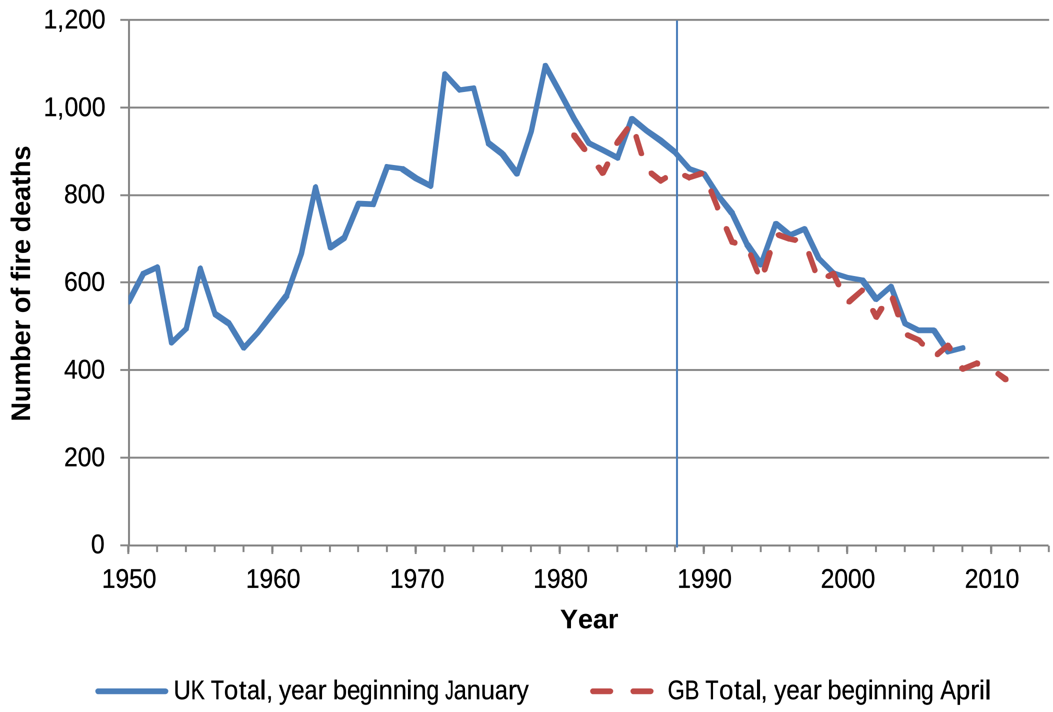


Figure 2 – Total number of fire deaths per year; collection of data shown for UK calendar years and GB fiscal years.[122] The vertical line represents the introduction of the Furniture and Furnishings Regulations 1988[48]

Statistics such as these should always be treated with considerable caution as it is easy to draw inferences with factors that happen to be of interest during the analysis. The area of interest of this thesis would naturally point one to note that there was a significant increase in the number of fire deaths during the period from 1950 to 1980, and that this coincides with the beginning of mass production and commercialisation of plastics such as polyurethane (1954), polypropylene (1957) and expanded polystyrene (1954). Additionally, the sustained decline may be considered to be relevant to the introduction of the Furniture and Furnishings Regulations in November 1988, which controlled the properties of these materials (generally altered using additives or surface applied treatments) where their use as furniture and furnishings was considered to be a significant contributor to the fuel load in the home and workplace.

However the period of increasing fire deaths also more generally coincides with the "baby boom" years when personal wealth increased dramatically post first and second world wars. Overlaying periods of recession onto the data hints that this might have a direct impact on the number of fire deaths also, but this too might be confirmation bias. It is also interesting to note that spikes in GDP growth coincide with some of the most marked increases in numbers of fire related deaths, Figure 3. In practice, there have been so many changes to fire safety and other related factors over this period that it is not currently feasible to separate, identify and quantify all of their respective impacts on the overall trend.

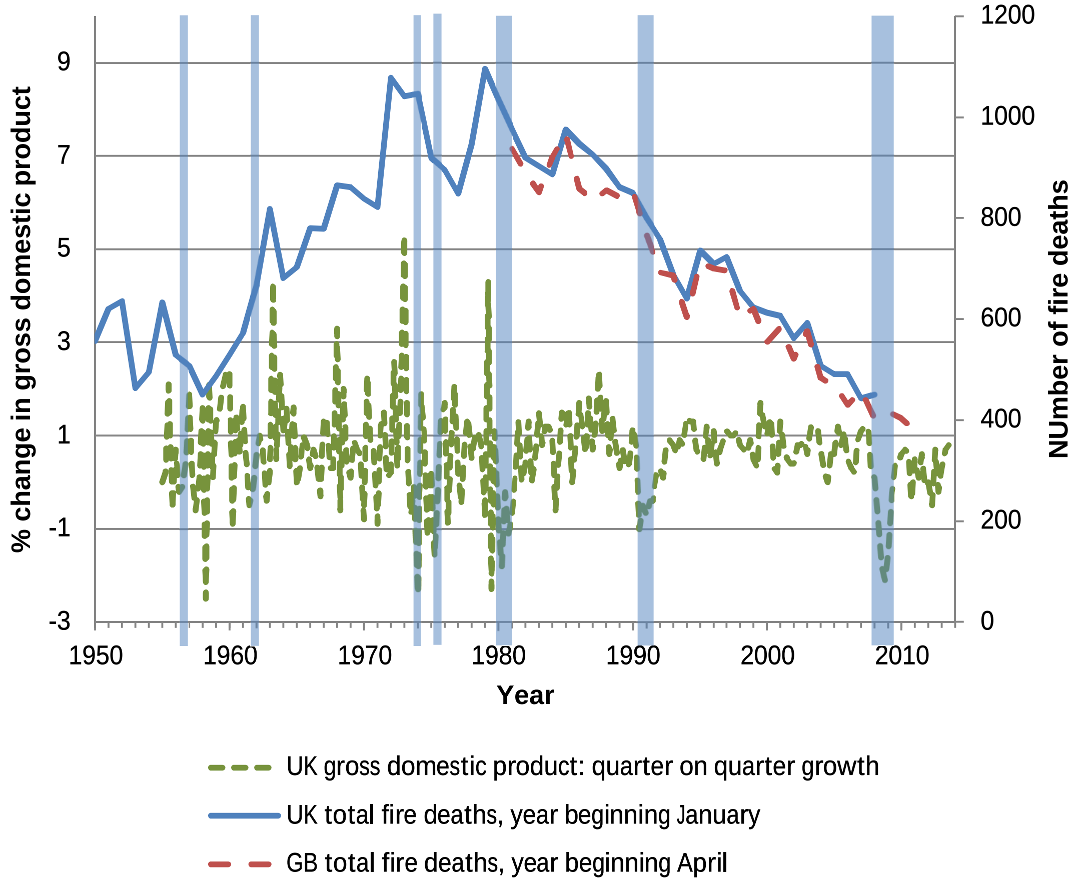


Figure 3 – Total number of fire deaths per year overlaid with change in UK Gross Domestic Product (quarter on quarter % change) and periods of recession in shaded areas[123]

Breaking down the data into broad categories of cause of death provides further indication of the way in which these causes have evolved over the last fifty years. However, this data has had to be collated from a number of individual sources because, as mentioned earlier, the method of data collection has varied considerably over this time and so the level of detail that is available for analysis has also varied. The data shown in Figure 4 indicates a marked increase in the proportion of fire deaths resulting from inhalation of toxic gas and smoke between 1951 and 1967.

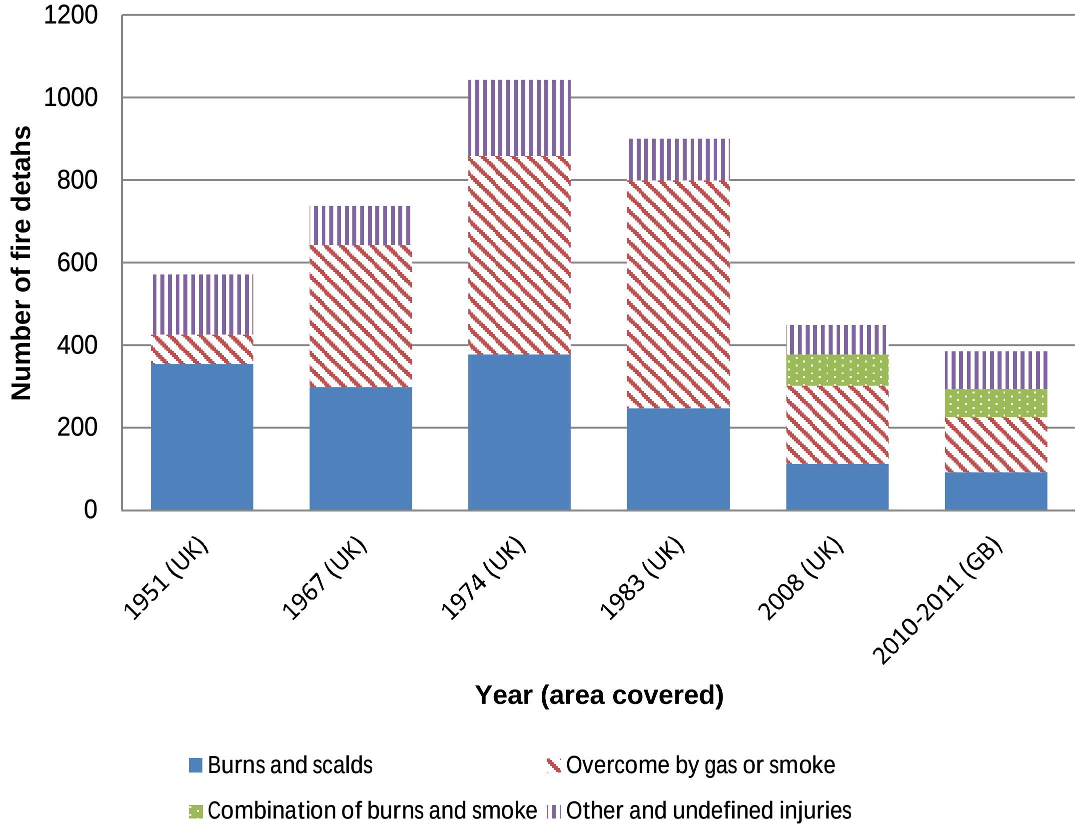


Figure 4 – Proportion of fire deaths arising from broad causes of death, based upon studies carried out by the Fire Research Station and the published data from the Department for Communities and Local Government. [11,122,124,125]

Detailed information on the circumstances surrounding fatal fires has not been collected at a national level for some years. Anecdotal evidence indicates that collection of data at this level of detail ceased simply due to the associated costs. However a survey of multi-fatality fires was carried out in 1968 which examined incidents occurring between 1960 and 1966. Of the 373 multi-fatality incidents occurring between 1960 and 1966, 368 were included in the study, covering 1000 deaths. The data shown in Table 2 (taken from the study) appears to indicate that asphyxiation (presumably largely through inhalation of toxic gases) is a more significant cause of death in multi-fatality incidents than in single fatality incidents (assuming a near linear growth in fire deaths between 1951 and 1967 in Figure 4). Table 3 indicates the relative significance of item first ignited between multi-fatality fires and all fatal fires. Here it is interesting to note that furniture and furnishings account for a significantly lower proportion of multi-fatality fires compared with all fatal fires. There are also highly contrasting figures for fires first involving clothing on a person (presumably due to the circumstances typically surrounding a person being set on fire, deliberately or accidentally) and fires starting on an unknown item (presumably as items become difficult to identify in longer incidents, where there is greater likelihood of more people succumbing). It would be extremely useful for these studies to have included a cross reference of item first ignited and cause of death, but unfortunately no data is available and this does not appear to have been carried out.

Location of casualties with respect to fire	Cause of death				Total deaths
	Burns	Asphyxiation	Other	Unknown	
At least one at seat of fire	158	105	27	14	304
Fire started elsewhere					
- No casualties trapped	48	198	9	5	260
- Casualties trapped	38	146	28*	7	219
Unknown	61	144	2	10	217
Total	305	593	66	36	1000

Table 2 – Causes of death of fatalities in multiple death fires (1960-1968) in relation to location of fatalities.[126] * includes 19 Fire Brigade personnel trapped by a falling wall

Material first ignited	No. multi death fires, 1960-1966	Percentage of total	No. fatal fires, 1966	Percentage of total
Crash (road, rail, air)	33	9.0	20	3.1
Explosion	28	7.6	29	4.5
Clothing on person	5	1.4	180	27.8
Furniture, furnishings	84	22.8	209	32.2
Other textiles	12	3.3	17	2.6
Liquids, fats	29	7.9	28	4.3
Escaping gas	3	0.8	6	0.9
Structural materials	11	3.0	29	4.5
Other	13	3.5	16	2.5
Unknown	150	40.7	114	17.6
Total	368	100	648	100

Table 3 – Material first ignited in multiple death fires, 1960-1966 and all fatal fires in 1966[126]

1.4.2. **London Data**

Some individual Fire and Rescue Services have chosen to maintain a higher quality of data than that which is gathered at the national level. In particular, London Fire Brigade continues to maintain an updated version of its real fire library which, among a great number of other categories, collects data on the specific circumstances of death in fatal fires.

It has already been stated that the data from London is assumed to be representative of the national data, however these datasets can be directly compared using the data categories from

Figure 4 to assess the relative ratio of the total number of fire fatalities falling into each category. This comparison indicates that whilst, as would be expected, these datasets are not identical in their proportions, they are reasonably similar.

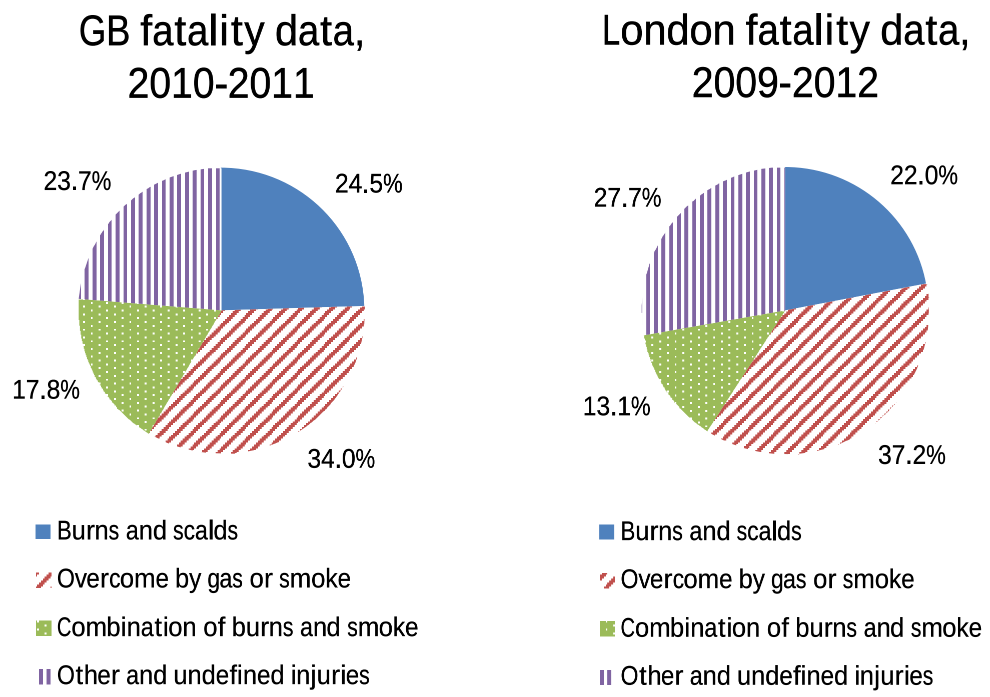


Figure 5 – Comparison of London data with national data. Proportions of all categories of data are comparable across the sets to within 5% of total number of fatalities

London Fire Brigade kindly provided data on all fatal fires between April 2009 and March 2012 which, aside from being anonymised, was ostensibly raw data, whereas previous data has only been accessible post-collation. This allowed factors of interest, such as cause of death, victim location (relative to fire origin), and material first ignited to all be cross referenced for the production of Table 4 to Table 6 below.

Table 4 indicates that, as might be expected, inhalation of gases, smoke and toxic fumes are responsible for a far greater proportion of the fire deaths that occur at locations remote from the fire origin. Within the room of fire origin, burns and smoke inhalation are equally significant as a cause of death. The data in Table 5 and Table 6 are much more disparate than in Table 4. Among the data points which have been identified are scenarios which are not controllable; the data points towards ignition of one's own clothing or bedding, but also smoke inhalation deaths arising from paper/cardboard and furniture fires. However grouping together materials which might be considered controllable, either through Furniture and Furnishing Regulations, Building Regulations or other potentially controlled chemicals, it appears that smoke inhalation is a significant contributor to fire related deaths.

	Burns	Combination of burns and inhalation of gas/ smoke	Inhalation of gas, smoke or toxic fumes; asphyxiation	Other or not known	Grand Total
Different room or compartment on floor of origin	9	5	**29**	7	50
Floor above origin		1	12	3	16
One floor below origin	2		1	1	4
Other or not known	6	2		12	20
Outside building, vehicle etc. of origin	2			2	4
Room, cabin or compartment of origin	**23**	16	**24**	27	90
Two or more floors above origin		1	5		6
Two or more floors below origin				1	1
Grand Total	42	25	71	53	191

Table 4 –Numbers of fatalities recorded by LFB between April 2009 and March 2012, cross-referenced by cause of death and fatality location. Values in bold red indicate where cross reference represents over 10% of total fatalities (excluding "other or not known")

	Burns	Combination of burns and inhalation of gas/smoke	Inhalation of gas, smoke or toxic fumes; asphyxiation	Other or not known	Grand Total
Bed/mattress*	3	1	4	2	10
Bedding	5	2	5	4	16
Chemicals in raw state*	1				1
Clothing	**15**	3	4	7	29
Cooking oil or fat		1	1	1	3
Foam - raw material only*			1		1
Gases*	2	1		1	4
Household paper/Cardboard			**8**	3	11
Internal Fittings*			1		1
Other or Not known	9	7	26	22	64
Paper, cardboard			1		1
Petrol/Oil products	6	3	2	10	21
Plastic - raw material only*	1	2	5		8
Rubbish/Waste material		2	2	1	5
Upholstered furniture*		1	**9**	1	11
Wiring insulation*		2	2	1	5
Grand Total	42	25	71	53	191
** Potentially controlled materials*	*7*	*7*	*22*	*5*	*41*

Table 5 –Numbers of fatalities recorded by LFB between April 2009 and March 2012, cross-referenced by cause of death and material first ignited. Values in bold red indicate where cross reference represents over 4% of total fatalities (excluding "other or not known")

	Different room or compartment on floor of origin	Floor above origin	One floor below origin	Other, unknown or not applicable	Outside building, vehicle etc. of origin	Room, cabin or compartment of origin	Two or more floors above origin	Two or more floors below origin	Grand Total
Bed/mattress	3					7			10
Bedding	4		1			**11**			16
Chemicals in raw state						1			1
Clothing	4	1	1	4	1	**18**			29
Cooking oil or fat	1					2			3
Foam - raw material only	1								1
Gases	1				1	2			4
Household paper/Cardboard	6					5			11
Internal Fittings		1							1
Not known	22	11	1	6	1	23			64
Paper, cardboard	1								1
Petrol/Oil products		1	1	10	1	7		1	21
Plastic - raw material only		1				1	6		8
Rubbish/Waste material	2					3			5
Upholstered furniture	5					6			11
Wiring insulation		1				4			5
Grand Total	50	16	4	20	4	90	6	1	191
** Potentially controlled materials*	*10*	*3*			*1*	*21*	*6*		*41*

Table 6 – Numbers of fatalities recorded by LFB between April 2009 and March 2012, cross-referenced by fatality location and material first ignited. Values in bold red indicate where cross reference represents over 4% of total fatalities (excluding "other or not known")

2. CASE STUDIES OF RECREATED BUILDING FIRES

Recreations and reconstructions have been used to support the investigation of major building fires for some years. This chapter will investigate the key findings from previously conducted research and reconstructions into fatal incidents. It is not the intention of this chapter to present all of the detailed methodology behind the various pieces of work as they are reported in a number of publications, reports etc. The detailed method will be covered for the work carried out by the author; the reconstructions of the fires at Wealmoor Atherstone in 2007 and Lakanal in 2009.

The principles and formulae given in ISO 13571 have been adapted to allow individual assessment of the factors responsible for the deaths in each of the fires examined. Calculations have been carried out (where data is available) and presented for the following:

- Asphyxia due to carbon monoxide, including effect of increased uptake due to carbon dioxide
- Asphyxia due to hydrogen cyanide, including effect of increased uptake due to carbon dioxide
- Incapacitation due to irritant gases (all gases summed together), including effect of increased uptake due to carbon dioxide
- Heat

The calculations have been carried out using the equations presented in chapter 1.3.3.

The fatalities examined naturally fall into two categories:

- Civilian casualties; those who are exposed to whichever hazards are present in an environment
- Fire fighter casualties; those who are exposed to heat but are isolated from the effects of toxic and irritant gases by virtue of their self-contained breathing apparatus

2.1. Stardust Disco

On 14th February 1981 at around 01:30, around 840 people were at a disco at the Stardust nightclub in Dublin when a fire was spotted in one of the seating areas. After a few minutes the fire had developed so quickly that in the ensuing rush to escape, 48 people died and 214 were injured.[127,128]

The Stardust Club was part of a complex built originally in 1948 as a food factory in the North Dublin suburb of Artane. In 1977/78 a portion of the building which had previously been used in part for the manufacture of chocolate was converted into an amenity centre. Originally intended for use for cabarets and concerts, it was subsequently used for discos. In general the area consisted of a dancing area, a small stage and seating area together with ancillary areas such as toilets, cloakrooms and bars.

The fire was first seen on the first seat of the back row in the west alcove around 01:30. It was spreading rapidly from seat to seat in the immediate area. The Tribunal into the fire concluded that the more probable explanation of the fire was that it was caused deliberately.[127]

Postmortem examinations of all the fatal victims from this fire and their toxicological results are presented in Table 7. A plan of the locations of the victims was prepared by the fire brigade, but unfortunately no record was kept of which victim was removed from which location, so it is not possible to make any analysis of the possible effect that victim location and/or actions might have had on exposure to fire temperatures and gases.

Victim No.	COHb (%)	HCN (Micrograms per 100ml blood)	Alcohol milligrams per 100ml	
			Blood	Urine
1	36	27.7	6.3	
2	25	11.2	25.8	
3	50	36.4	125.1	
4	31	13.5	2.1	
5	26	17.0	Nil	
6	14	Blood unsuitable	90.5	
7	39	13.2	36.3	
8	25	53.9	Nil	
9	40	7.6	145.1	
10	30	17.4	Nil	
11	26	16.3	Nil	6.5
12	20	19.1	207.8	287.4
13	42	123.3	211.0	
14	39	58.6	14.0	
15	27	7.1	212.5	249.9
16	45	19.5	79.2	103.6
17	36	14.6	92.7	134.2
18	34	72.1	11.7	14.7
19	10	4.5	126.4	

Victim No.	COHb (%)	HCN (Micrograms per 100ml blood)	Alcohol milligrams per 100ml	
			Blood	Urine
20	27	39.7	72.9	109.1
21	33	10.5	Nil	Nil
22	36	66.7	115.0	133.5
23	59	30	155.5	140.9
24	20	8.4	152.0	244.3
25	20	12.4	148.9	175.6
26	41	12.7	129.7	
27	56	11.4	90.8	126.5
28	30	33.1	1.9	4.9
29	39	11.7	4.4	
30	42	26.4	102.5	143.6
31	15	12.1	103.8	
32	55	100.5	175.6	
33	48	28.8	124.7	
34	29	49.2	63.7	
35	50	122.7	158.8	
36	No data	No data	No data	No data
37	18	9.3	92.8	111.0
38	50	153.0	23.9	
39	3	6.5	101	187.2
40	30	40.7	Nil	13.3
41	24	59.2	123.4	164.8
42	56	37.4	195.3	294.2
43	61	61.8	178.7	233.3
44	42	22.7	Nil	
45	46	5.0	74.4	
46	No data	No data	No data	No data
47	0	3.9		

Table 7 – Summary of toxicological findings from postmortem examination of victims of Stardust Disco fire

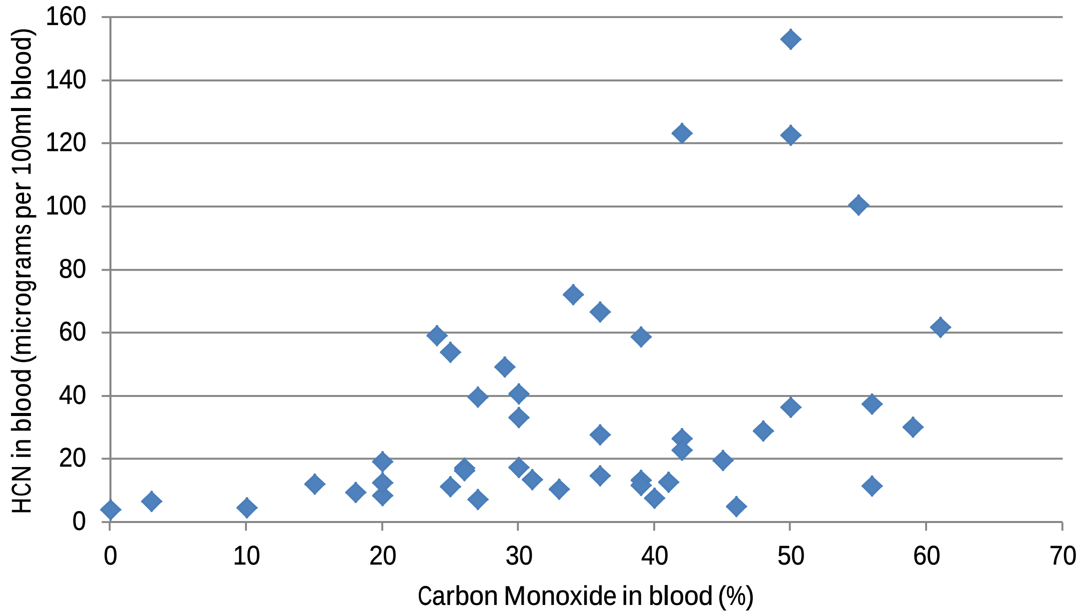


Figure 6 – Carbon monoxide and hydrogen cyanide data from Table 7, presented graphically

The tribunal of enquiry considered that carbon monoxide concentrations above 40% should be considered lethal and therefore relevant to cause of death, whilst a cyanide concentration over 100 micrograms per 100ml blood was also considered lethal. Concentrations of carbon monoxide between 20% and 40% were considered to indicate cause of death being a combination of the effects of heat and smoke inhalation, whilst lower concentrations were considered to indicate heat being the principle cause of death. When compared with modern figures for death due to asphyxiant gases (50% COHb and 3 μg CN/ml – or 300 μg CN per 100 ml), the data would tend to indicate that carbon monoxide was more significant than hydrogen cyanide in this incident. However, there is no information available concerning the interval between death and analysis of blood samples, so it is possible that actual hydrogen cyanide levels may have been higher at the time of death. None of the alcohol concentrations were considered to be sufficiently high to have contributed directly to any of deaths (i.e. via toxicity). However, intoxication is likely to have a played a role in the ability of the victims to effect their own evacuation.

2.1.1. **Reconstruction and Test Results**

The west alcove of the Stardust Disco and its main constructional features were included in a full-scale reconstruction of the incident. The reconstruction involved the accurate reconstruction of approximately 20% of the west alcove in the region where the fire was first discovered. Seating was installed in precisely the same positions, materials were selected to be identical in performance, and geometric configuration were as close as possible to those existing at the Stardust Disco at the time of the fire. This was to allow assessment of the way in which the fire suddenly developed from a relatively small fire (described as a curiosity by eye-witnesses) to a very rapidly growing large fire (causing panic among all those in the Stardust Disco at the time of the fire). One of the particular materials of interest as part of this recreation of the area of origin was the carpet tile used to line the walls of this part of the Stardust Disco. The layout of the Stardust rig and locations of the instrumentation relevant to this study are shown in Figure 7.

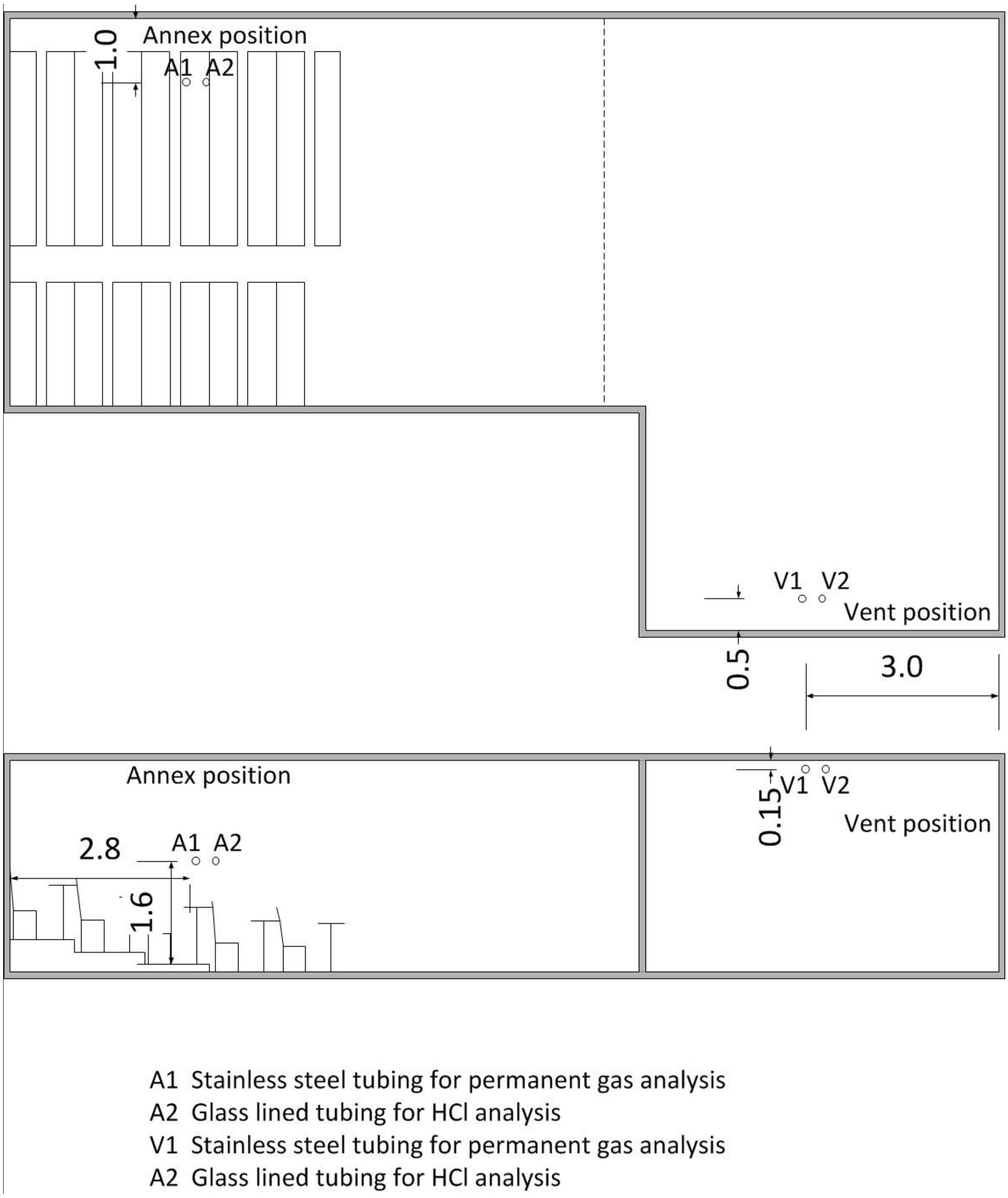


Figure 7 – Stardust reconstruction rig layout, showing locations of gas sampling points

The reconstruction was started by lighting sheets of newspaper placed beneath seats in the rear tier. The initial attempts at ignition proved abortive and after a delay the fire was re-ignited using five crumpled double sheets of newspaper. Shortly after one minute, the carpet tiles on the wall were involved and events moved very quickly. By one and a half minutes, lateral spread at ceiling level producing downward radiation, combined with flaming droplets providing the pilot ignition source, had involved the whole of the back row of seats. Flashover was reached in less than two minutes and the recorded events fully confirmed and, to some extent, exceeded the expected rapid growth rates predicted from the preliminary tests. The fire development shown in Figure 8 to Figure 11 is from a set of stills across 25 seconds of the video footage of the reconstruction fire.

Figure 8 – Still from BRE/FRS video of Stardust reconstruction (see Appendix A), fire initially developed on seating and involving nearby carpet tiles lining walls

Figure 9 – Still from BRE/FRS video of Stardust reconstruction (see Appendix A), downward radiation causing pyrolysis of seat covering

Figure 10 – Still from BRE/FRS video of Stardust reconstruction (see Appendix A), rapid fire development as materials ignite (flashover)

Figure 11 – Still from BRE/FRS video of Stardust reconstruction (see Appendix A), full involvement of rig and flame extension outside

During this period of rapid growth culminating in flashover, temperatures in the hot gas layer below the insulating ceiling exceeded 1300°C. As more of the fuel became involved it was estimated that heat output approached 20 – 25 MW. By this stage the fire was ventilation controlled and so incomplete combustion was producing, among other things, large quantities of soot and black smoke. The data from the FRS report into the fire is shown in Figure 12. No electronic record of the data remains, so it has been necessary to recreate the data manually, so that this can be used for the FED analysis later. This has been achieved using free-to-use online software which can be used to generate coordinates for the lines on images of graphs.[129] The plot of the recovered data is shown in Figure 13.

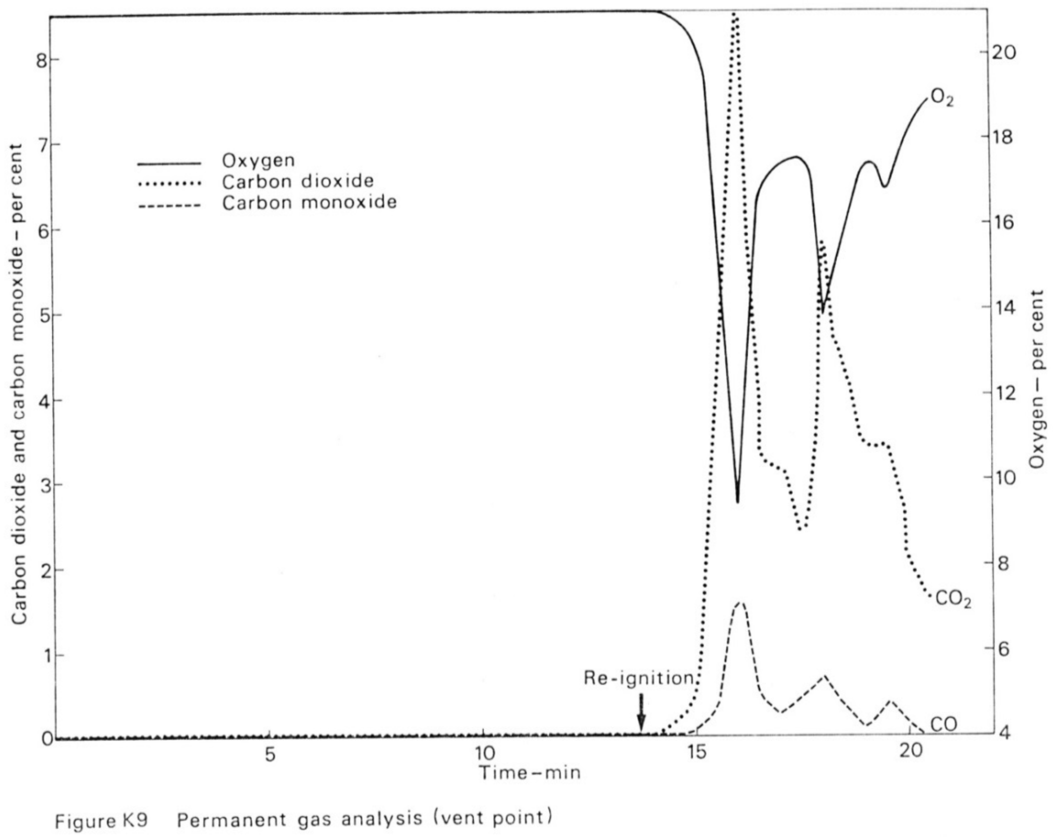


Figure 12 – Figure K9 from the FRS report into the Stardust Disco fire[128], showing the gas analysis data collected from the sampling points in the full-scale reconstruction.

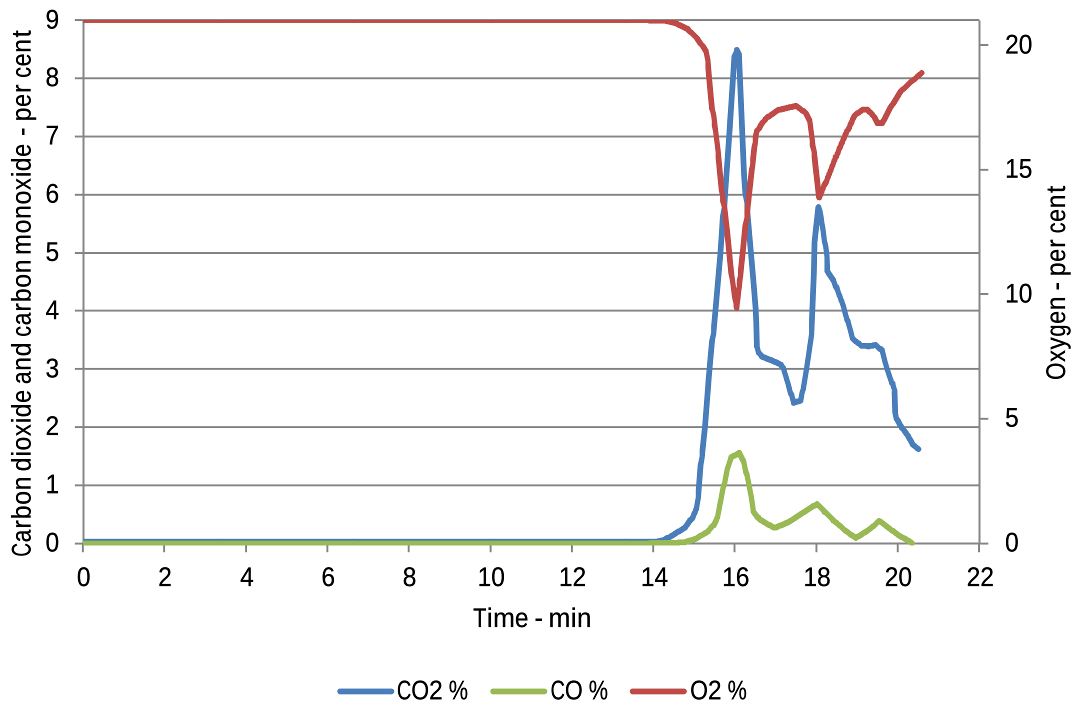


Figure 13 – Excel plot of data manually "recovered" from Figure 12

2.1.2. **Sequence of Events Relevant to Analysis**

Analysis of the sequence of events relevant to the victims of the Stardust Disco fire is difficult as it is not known where the victims were recovered from and so no relationship can be drawn between likely movements or location at the point of incapacitation and the potential severity of conditions.

It is known that the fire started around 01:30 and that the fire was relatively small, causing little concern to the people in the vicinity, until its growth rate started to increase dramatically around 01:42. Panic ensued around this time and the fire brigade were called at 01:43. Various exits from the building are known to have been found to be locked shut at this time and were not opened until 01:45. Once these exits were opened, those people that were able to get out did so by 01:46.

2.1.3. **FED Data from Experimental Data**

A number of assumptions and additional analyses had to be made in order to generate a dataset suitable for hazard analysis according to ISO 13571. In particular, whilst a large quantity of data had been collected within the fire area (annex measurements); examining radiant fluxes, temperatures, mass loss and other aspects of fire development, the data collected which was relevant to the actual conditions to which the victims of the fire were exposed (vent measurements) was patchy.

Given that the deaths arising from this fire may have resulted from exposure to heat, fire gases, or a mixture of both, it was considered important to have as complete a data set as possible for inclusion into the calculations. The data used was as follows:

- Oxygen, carbon dioxide and carbon monoxide concentrations were taken from continuous measurements collected at the annex and the vent (i.e. complete data).
- Hydrogen cyanide and hydrogen chloride data for the annex have been taken from grab samples analysed using Draeger tubes (i.e. actual data but average figures over large time intervals).
- Hydrogen cyanide data for the vent has been calculated based upon data from the grab samples and dilution of carbon monoxide between the annex and vent (assuming same dilution occurs for both).

- Hydrogen chloride data for the vent has been calculated based upon nephelometry sampling at both the annex and vent (giving indication of changing losses between measurement points as concentration generated changes) and the grab samples collected at the annex.
- Heat flux and temperature data for the annex have been taken from a heat flux meter located on the tiers of seating (on a seat, facing upwards) in the annex and a thermocouple 1 metre below the ceiling in the annex respectively.
- Heat flux and temperature data for the vent have been from a heat flux meter near the vent (1m above the floor, facing upwards) and a thermocouple at ground level in the annex. No temperature data was available near or at the vent so it has had to be assumed that this will be a suitably comparable measurement.

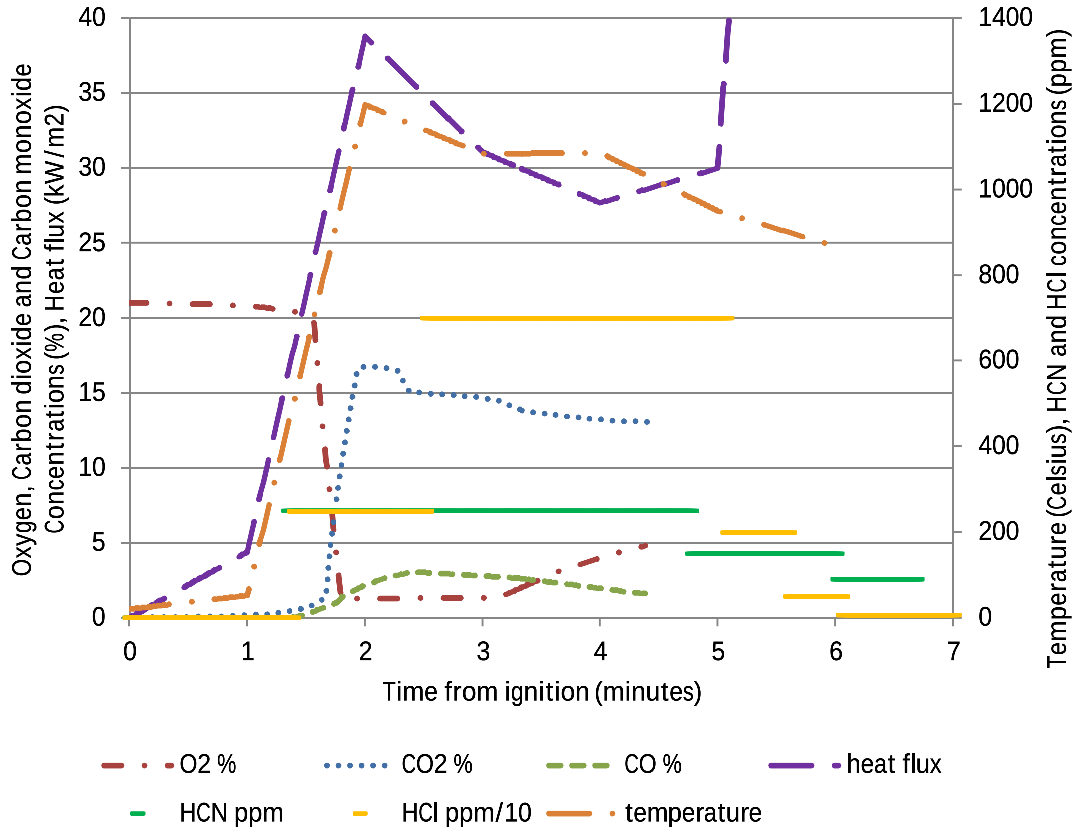


Figure 14 – Data used from Stardust reconstruction annex point measurements for FED calculations (N.B. HCN and HCl were collected as discrete samples to provide average concentration over set periods, so data is presented as discrete periods)

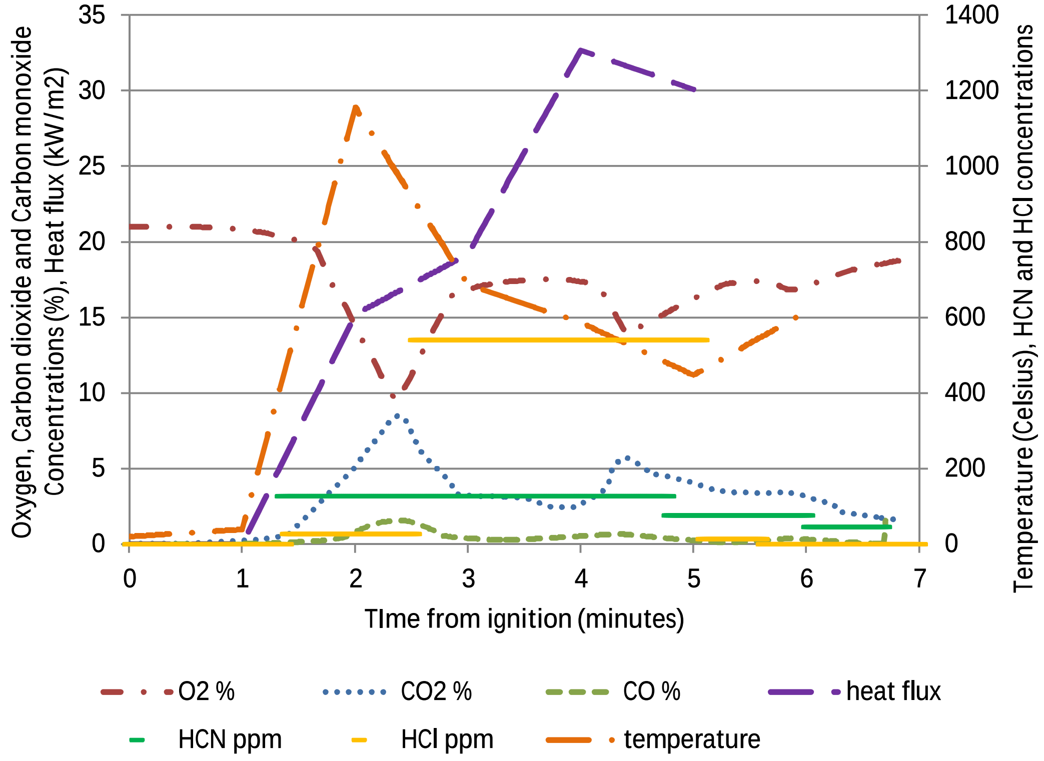


Figure 15 – Data used from Stardust reconstruction vent point measurements for FED calculations (N.B. HCN and HCl were collected as discrete samples to provide average concentration over set periods, so data is presented as discrete periods)

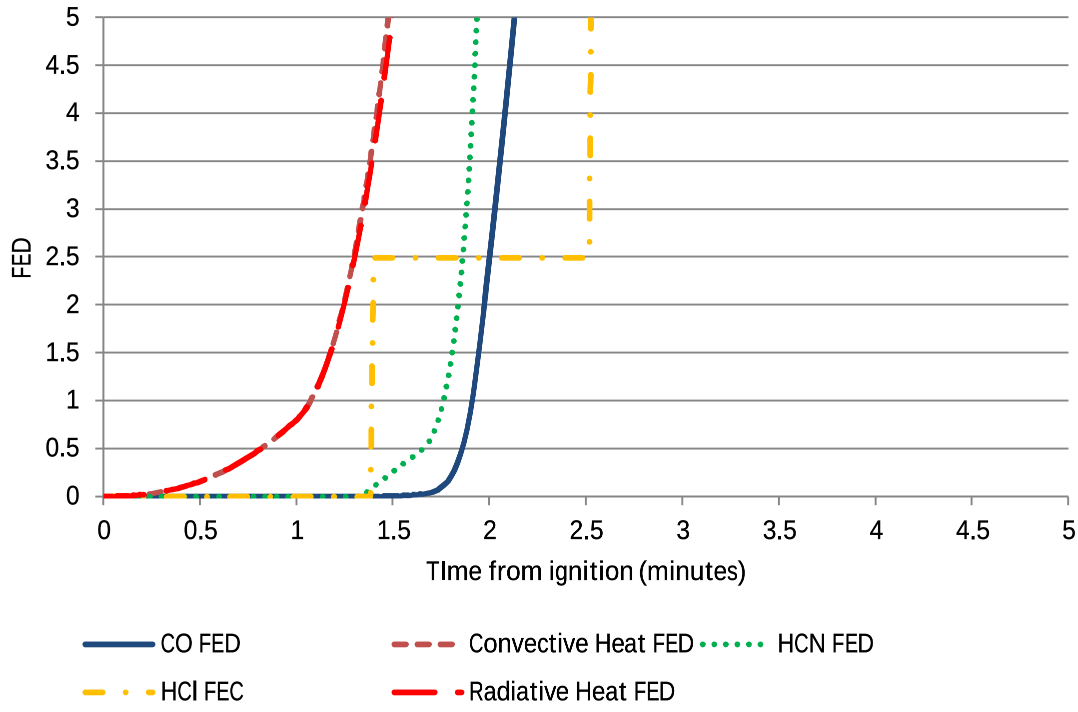


Figure 16 – FED values calculated using ISO 13571 method based upon Stardust reconstruction annex point measurements. As previously discussed, FED>1 is shown for indication and should not be considered an accurate representation of increasing hazard

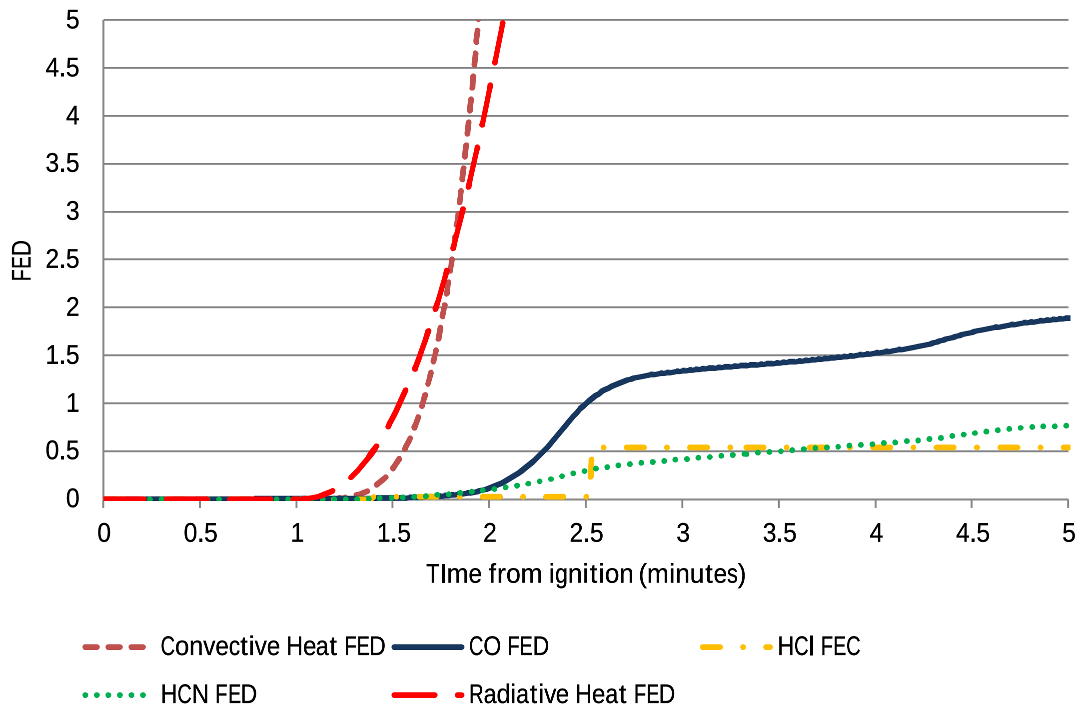


Figure 17 – FED values calculated using ISO 13571 method based upon Stardust reconstruction vent point measurements. As previously discussed, FED>1 is shown for indication and should not be considered an accurate representation of increasing hazard

The analysis in both cases indicates that heat is the dominant factor in the overall hazard. It is interesting to note that radiant and convective heat appear to be equally significant at the annex point (near the origin of the fire) whereas convective heat becomes the dominant factor further away at the vent point. Given the gas concentrations at the annex, the significance of radiant heat is likely to be attributable to the optical density of the smoke and its resultant emissivity of thermal radiation. Reports from the work carried out certainly indicate that extremely thick, black smoke was produced in very large quantities when the reconstruction was carried out.

It is interesting to note that hydrogen cyanide was the dominant toxicant at the annex point in Figure 16 (nearer the seat of the fire) whereas carbon monoxide was the dominant toxicant at the vent point in Figure 17 (away from the seat of the fire). This highlights the difference in proportion of carbon monoxide to hydrogen cyanide at these two locations (visible but less apparent in Figure 14 and Figure 15).

2.2. Maysfield Leisure Centre

On 14th January 1984 a fire broke out in the Maysfield Leisure Centre, East Bridge Street, Belfast. The fire started in an equipment store adjacent to the main sports hall at around 13:35. By 13:45 the smoke and toxic gases produced by the fire were sufficient to have caused the deaths of six of the people who were in the building at the time of the incident.[130]

At the time of the fire, around 300 people were in the building, of which 150 were in the main sports hall either watching or competing in a judo competition. None of the people in the main sports hall were overcome by the fire. Whilst conditions were reported as being smoky and likely to have been unpleasant, everyone in the main sports managed to escape the building safely. Of the six people that were overcome by the fire, one had been using the squash courts (one of six squash court users at the time) and five had been using a darkened room being used for photography (there were no survivors from this room). One squash court user was incapacitated during the course of the incident, collapsed and had to be dragged to an exit by another person.

The layout of the equipment store is shown in Figure 18; the labelled contents as follows:

1. Crash mats
2. Squash Court Corridor
3. Roller shutter doors
4. Keep fit mats
5. Trampoline
6. Judo mats
   a. 40
   b. 25
   c. 15 on end
7. Mini trampoline
8. Horse
9. Badminton stands
10. Low beam
11. 3 Phase electrical switches
12. Hockey posts
13. Badminton nets and posts
14. Gymnastic beam
15. Goal posts
16. Wooden pallets
17. Store doors
18. Main hall

PLAN 5

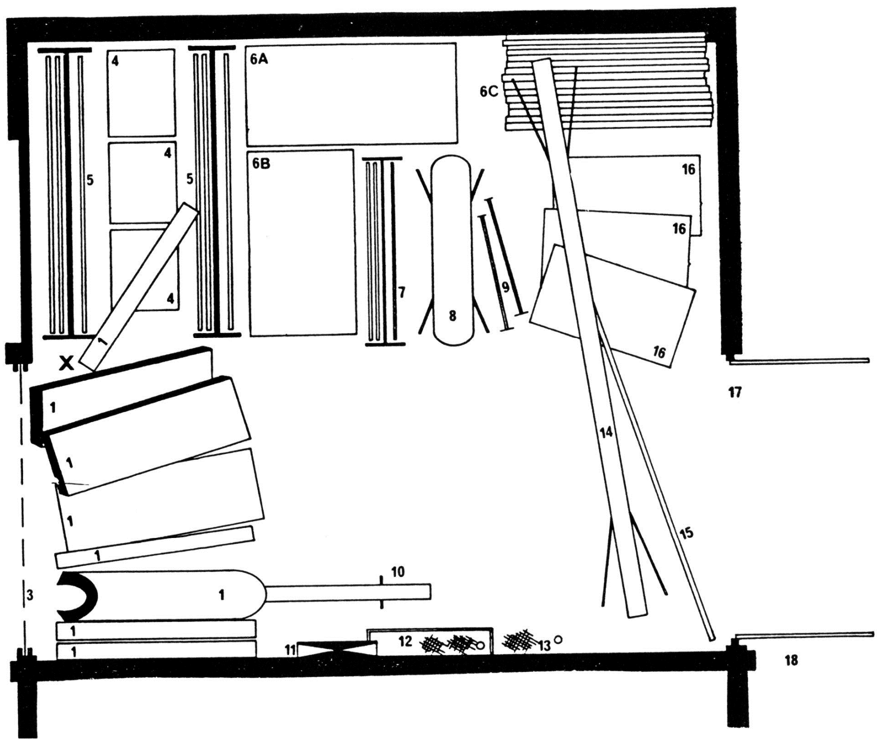


Figure 18 – Plan number 5 from the Boyce report[130] (Crown Copyright) showing the contents of the equipment store

The physical dimensions of the equipment store and other relevant features are as follows:

- The internal dimensions of the equipment store were 6.3m by 6.0m by 2.77m high.
- The equipment store communicated with the main hall via a set of double doors measuring 2.5m by 2.5m high. These doors were considered to have been closed or nearly closed prior to the fire. Reports indicate these doors were opened by people investigating the initial fire but the relatively little damage (limited to smoke staining in a well-defined plume) above these doors shown in photographs indicates that these doors were probably closed throughout the majority of the fire.
- The store communicated with a long corridor measuring 32.5m by 2m in area. The overall height of the corridor was 2.77m to the underside of the floor slab but a suspended ceiling was installed at 2m. The suspended ceiling was constructed of wooden slats spaced apart and therefore did not significantly alter the overall volume of the corridor.
- The store communicated with the long corridor via a roller shutter door 2.5m wide and 2.0m high.

The store housed switches and drive motors associated with electrical apparatus above the main hall. Lighting was provided by three tungsten lamps. The building structure was predominantly a steel frame encased in concrete with reinforced concrete floors. There were some loadbearing brick walls and a number of non-loadbearing brick walls. As such the fabric of the building did not contribute significantly to the toxicity of the fire that was produced. The internal surfaces of the equipment store and the corridor were all brickwork. The contents of the equipment store are detailed in Table 8.

Item description	Number	Relevant material/s
Judo mats	80	High density polyester foam crumb with heavy PVC covering and rubberised hessian underside
Crash mats	8	Low density polyurethane foam with cotton canvas covering
Keep fit mats	3	Understood to cut from judo mats
Trampoline	2	Nylon components
Mini trampoline	1	Nylon components
Vaulting horse	1	Leather
Gymnastic beams	2	Timber
Pallets	3	Timber

Table 8 – Items and their constituent materials in the Maysfield Leisure Centre equipment store at the time of the fire

The details of the casualties are shown in Table 9 and their corresponding movements/locations are shown in Figure 19.

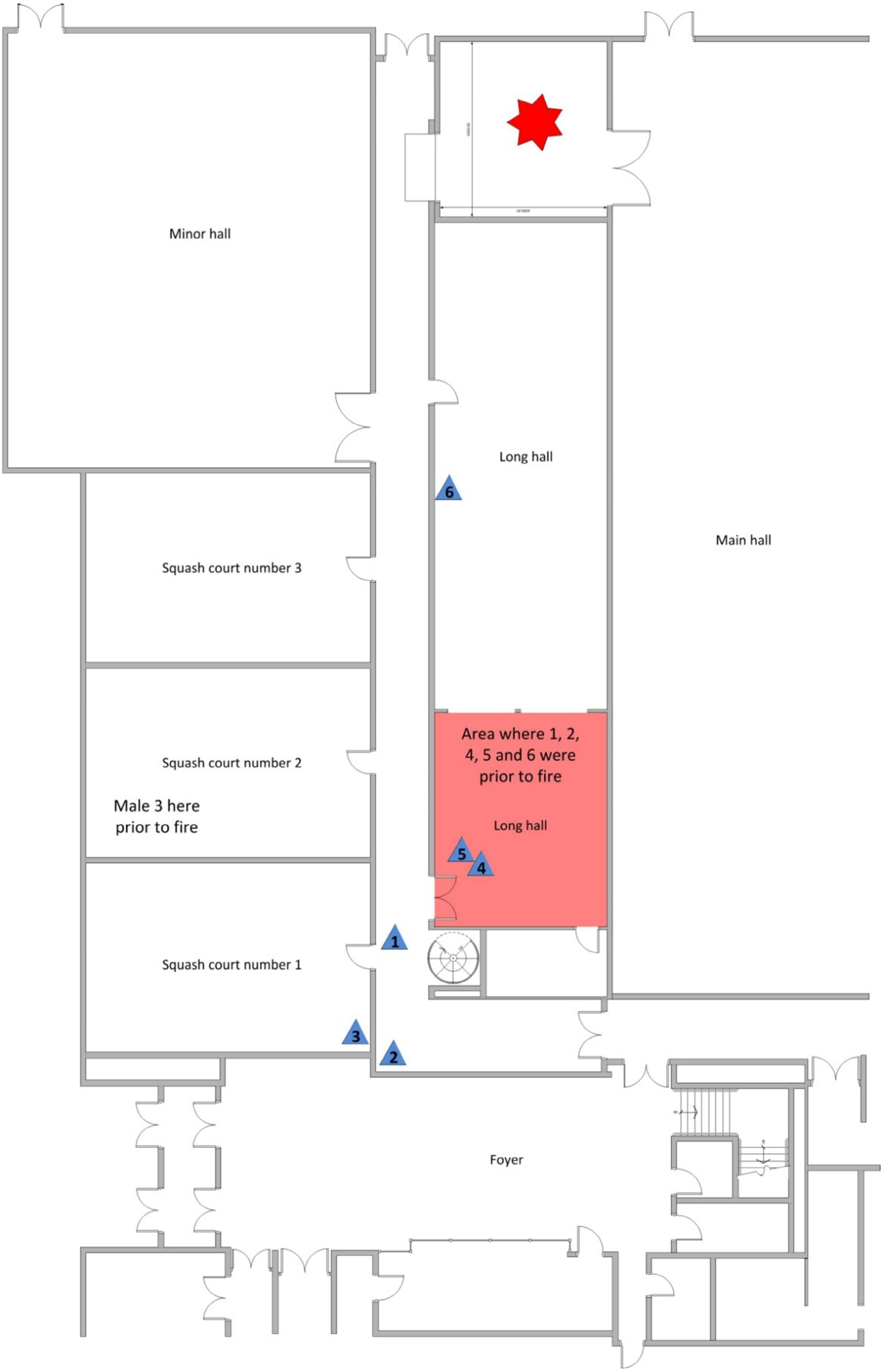


Figure 19 – Plan showing the relevant portion of Maysfield leisure centre and the locations of the bodies (see Table 9). The red star indicates the room where the fire occurred and the red shaded area indicates the area used as a darkened room

Plan No.	Gender	Age	Location/ role at ignition	Outcome and location found, if applicable	COHb [*1] (%)	COHb [*2] (%)	HCN [*3] (µg/100 ml)	Notes
1	Female	25	Long hall	Deceased, corridor	57	41	322	
4	Female	7	Long hall	Deceased, long hall	54	48	78	
5	Female	9	Long hall	Deceased, long hall	64	48	97	
6	Male	64	Long hall	Deceased, long hall	39	29	205	*4
2	Male	33	Long hall	Deceased, corridor	48	38	243	*4
3	Male	17	Squash court 2	Deceased, squash court 1	43	34	567	
	Male	25	Fire Fighter	Minor smoke inhalation				
	Male	Not known	Squash court 3	Incapacitated, corridor				
	Male	Not known	Squash court 3	Minor smoke inhalation				

*1 – Carboxyhaemoglobin concentration measured by State Pathologist Department during postmortem examination.
*2 – Carboxyhaemoglobin concentration measured by Department of Forensic Medicine and Science, Glasgow University, one week later than postmortem examination
*3 – Measured by Department of Forensic Medicine and Science, Glasgow University, one week later than postmortem examination
*4 – Carbonyl compounds were found in blood samples

Table 9 – Details of casualties resulting from fire at Maysfield Leisure Centre

In all cases for the fire victims there were:

- no signs of heat damage to respiratory tracts
- extensive congestion of the lungs (N.B. Soot is not specifically mentioned in any of the reports available in relation to this incident.)
- no significant injuries; only minor injuries consistent with people falling over in smoke were noted

The toxicological data for the deceased indicates a variety of conditions occurred with respect to the relative significance of carbon monoxide and hydrogen cyanide, with relative concentrations of carbon monoxide and hydrogen cyanide appearing to vary significantly. The interval between the postmortem examination and the measurements by the Department of Forensic Medicine and Science is likely to have had a far greater impact on detectable cyanide concentrations than carbon monoxide, so it would be reasonable to expect that hydrogen cyanide played a far more significant role in this fire than the toxicological results would initially indicate.

2.2.1. **Reconstruction and Test Results**

Experimental work was carried out by the Fire Research Station[131] to examine the incident and the way in which the burning of various materials during the incident contributed to the deaths. The specific items of interest were the judo mats, crash mats, trampoline nets and keep fit mats which all would release nitrogen containing materials.

Ignition tests showed that whilst all of the materials identified in Table 8 above would burn, there was significant variation in their susceptibility to ignite, with some materials burning readily when subjected to a match flame, whilst other materials would only burn when exposed to a substantial incident heat flux. Crash mats were found to be the only item in the equipment store which would ignite from a smouldering source (a lit cigarette).

Two full-scale tests were carried out using a rig to represent the storeroom and adjacent corridor, Figure 20. The rig was instrumented to allow measurement of gas temperatures, smoke optical density, gas velocities and gas concentrations (continuous measurement of CO, CO_2, and O_2, grab samples for HCN and HCl). One sample of gas was also successfully taken from the flaming test for full analysis using GC-MS.

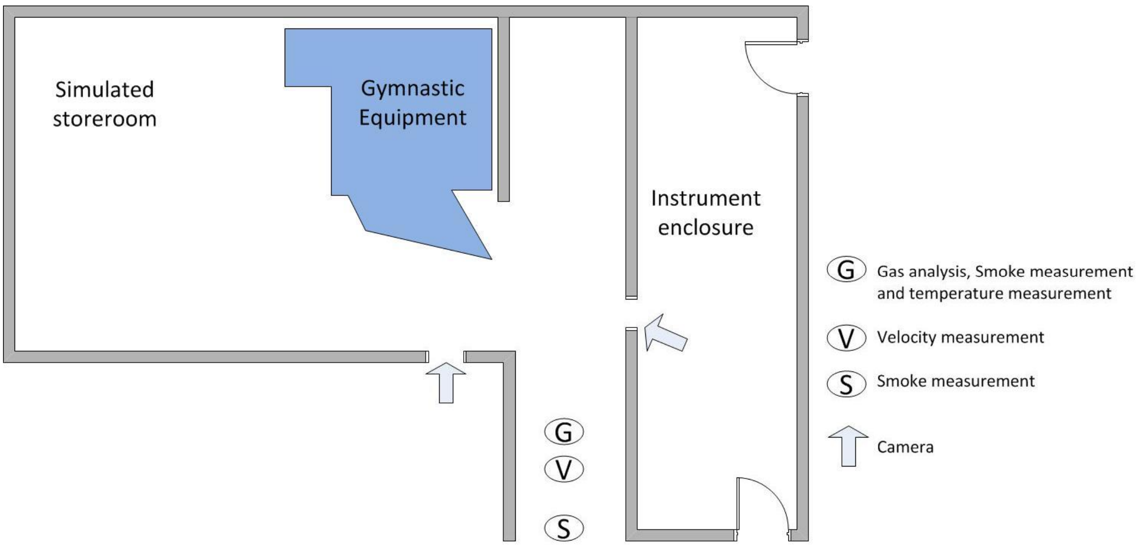


Figure 20 – Figure 2 from the FRS report into the Maysfield fire[131], showing the layout of the reconstruction rig used to simulate the fire. Note that the rig was designed to be mirror image of the actual layout in the incident

The first test was a smouldering test (ignited using a lit cigarette) on a single crash mat. The test was carried out to investigate the timescales that would have been needed for the smouldering fire to lead to a flaming fire and whether this was compatible with timescales and witness testimony from the incident. The test revealed that a strong and unpleasant smell would have been apparent to any people in the vicinity well before any life-threatening conditions presented themselves. This indicated that a smouldering fire would have allowed sufficient timescales between detection and onset of untenable conditions to have allowed building occupants to escape safely, Figure 21.

Figure 21 – Plate number 1 from the FRS report into the Maysfield fire[131] (see Appendix A) showing the smouldering test on the crash mat 20 minutes after ignition

The second test was a full-scale flaming test using a set of contents for the rig which were designed to be representative of the contents involved in the actual fire. The fire is reported to have developed quickly; the timeline of fire development is shown in Table 10. The initial fire during this test is reported to have appeared to burn cleanly, with a little pale smoke. As the fire size increased and more fuel became involved, the quantity of smoke also increased.

Figure 22 – Plate number 7 from the FRS report into the Maysfield fire[131] (see Appendix A) showing the full-scale flaming test 4 minutes 30 seconds after ignition

Figure 23 – Plate number 12 from the FRS report into the Maysfield fire[131] (see Appendix A) showing the amount of smoke issuing from the full-scale flaming test 7 minutes after ignition

Time from ignition (mins:secs)	Description
00:00	Ignition by application of match flame to crash mat
02:00	Flames reaching top of vertical edge of crash mat; smoke still light in colour
02:45	Flames clearly visible above crash mats
03:00	Flames clearly visible approximately 0.5m above crash mats, but still only one crash mat involved; smoke still light colour but beginning to layer in room
04:00	Flames near ceiling and distinct smoke layer in room and emerging in corridor; smoke beginning to darken; still only one crash mat involved.
04:15	Rapid fire spread
04:30	Flames involve second crash mat
05:00	Third crash mat and adjacent pile of judo mats involved; large quantities of black smoke beginning along upper part of corridor
05:15	Plume at 500°C and 2.5 m/s, visibility in smoke 0.5m
06:00	Most severe conditions: 6% oxygen, 3.5% CO, 15% CO_2, 1700ppm HCN, 3100ppm HCl

Table 10 – Description of fire development during Maysfield Leisure Centre flaming fire test

	Discrete sampling		Continuous sampling		
Sampling time (minutes after ignition)	HCN ppm	HCN ppm	O_2 %	CO_2 %	CO ppm
4	3	3	20.17	0.11	0
6	1700	1700	15.05	5.69	7042
8	680	680	8.034	8.99	17223
10	660	660	9.21	8.57	21191

Table 11 – Hydrogen cyanide and hydrogen chloride concentrations in samples taken from flaming test, with corresponding values taken from continuous data (see Figure 24)

It was noted in the report that it was difficult to fully understand the mechanism by which increasing amounts of smoke were being produced by the fire. However, a note was made that the increase in smoke concentrations was possibly occurring when PVC covers on the judo mats became involved. It was also pointed out that PVC is normally difficult to ignite with a small flame, but happens when the severity of the fire is sufficient to force its involvement.

The gas analysis data gathered from the reconstruction is shown in Figure 24. No electronic record of the data remains, so it has been necessary to recreate the data manually, so that this can be used for the FED analysis later. This has been achieved using free-to-use online software[132] which can be used to generate coordinates for the lines on images of graphs. The plot of the recovered data is shown in Figure 25.

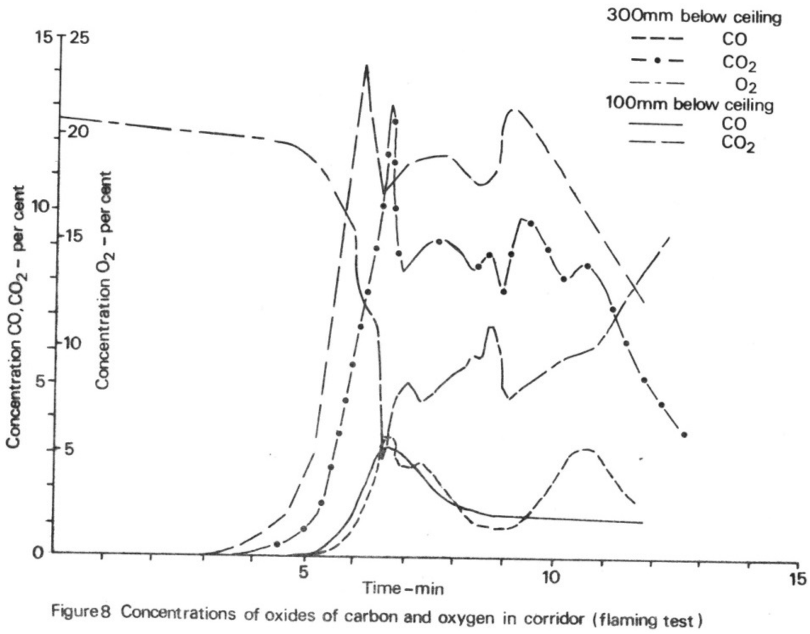


Figure 24 – Figure 8 from the FRS report into the Maysfield fire[131] (see Appendix A), showing the gas analysis data collected from the sampling points in the reconstruction.

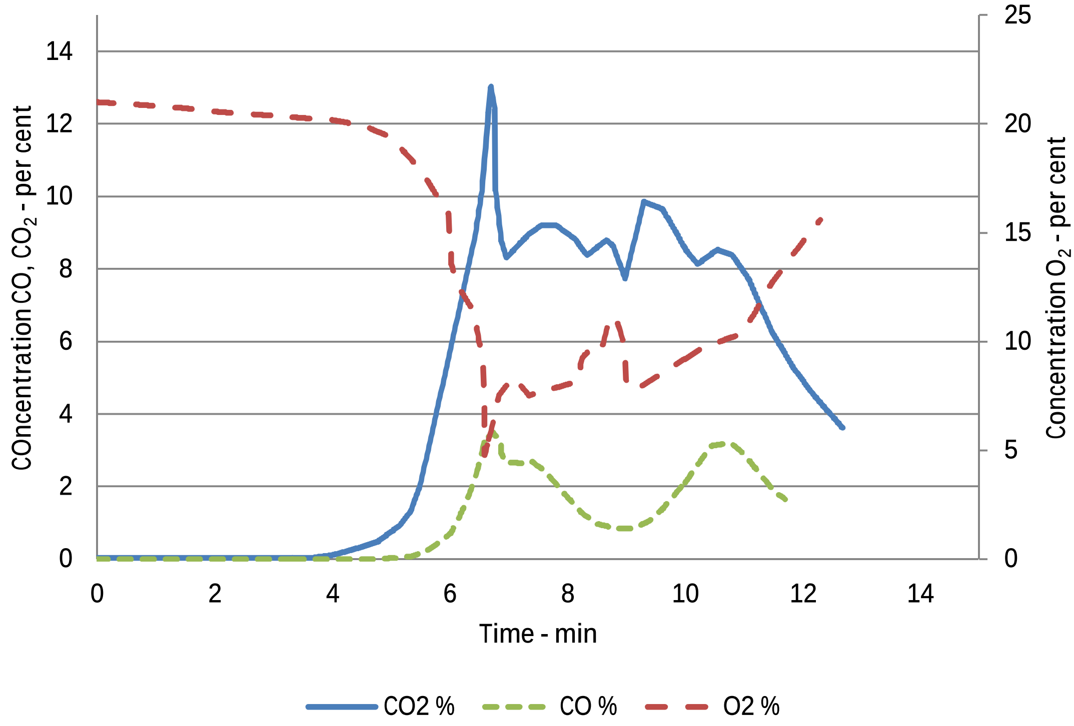


Figure 25 – Excel plot of data manually "recovered" from Figure 24 (N.B. Only data for 300mm below the ceiling has been used)

The sample taken at seven minutes from ignition and subjected to analysis using gas chromatography-mass spectrometry indicated that a wide variety of chemical species were present in the smoke, some of which were toxic or irritant gases, whilst others were flammable gases, presumably present as a result of pyrolysis of the fuel load and incomplete combustion taking place. The results from the GC-MS analysis can be seen in Table 12. Given that these results only cover a single point in time, and the complexity of the interactions responsible for their production, it is not possible to make assumptions about concentrations of the vast majority of the species and apply these to the continuous data for CO, CO_2 and O_2. However, the hydrogen cyanide data can be extrapolated against the concentration of CO based upon the work of Purser.[111,133]

MS interpretation	Approximate concentration (ppm)
Methane	16
Acetylene	640
Ethylene	115
Ethane	81
Propene	47
Hydrogen Cyanide	1870
Propane	208
Chloroethylene	20.2

MS interpretation	Approximate concentration (ppm)
Acetaldehyde	26.8
Chloroethane	0.16
Butane	4.10
Acetonitrile	177
Acetone	65.2
Acrylonitrile	95
Pentene	2.66
Methacrylonitrile	39
Benzene	400
Crotonitrile	56.4
Pyridine	35.7
Toluene	24.2
Xylene	3.5
Styrene	32.8
Benzonitrile	119
Methyl Styrene	17.8
Indene	20.7
TOTAL	4115

Table 12 – Species identified from gas chromatography-mass spectrometry analysis of sample taken from flaming test at 7 minutes from ignition, in order of retention time

2.2.2. Sequence of Events Relevant to Analysis

None of the victims of this fire were initially located in the room of fire origin or in the corridor which became filled with fire gases during the course of the incident. Of the six victims, two were found in the corridor directly connected to the room of fire origin, one was in a squash court but known to have passed through the corridor and the remaining three were all in the long hall; a large room connected to the corridor at two points.

The reconstruction data analysed below is for gas concentrations in the hot smoke layer in the corridor outside the room. Given the layout of the building and the limited opportunities for fresh air entrainment and dilution of the gas layer during it passage through the building, it is assumed that the victims were all exposed to gas concentrations equal to those measured during the course of the reconstruction.

The times to incapacitation and death of all six victims are therefore considered to be directly linked to the time of ignition of the fire, and therefore the time of ignition of the reconstruction.

2.2.3. **FED Data from Experimental Data**

FED calculations have been carried out using the data presented in Figure 25 and the temperature data from the reconstruction. The results of these calculations are shown in Figure 26.

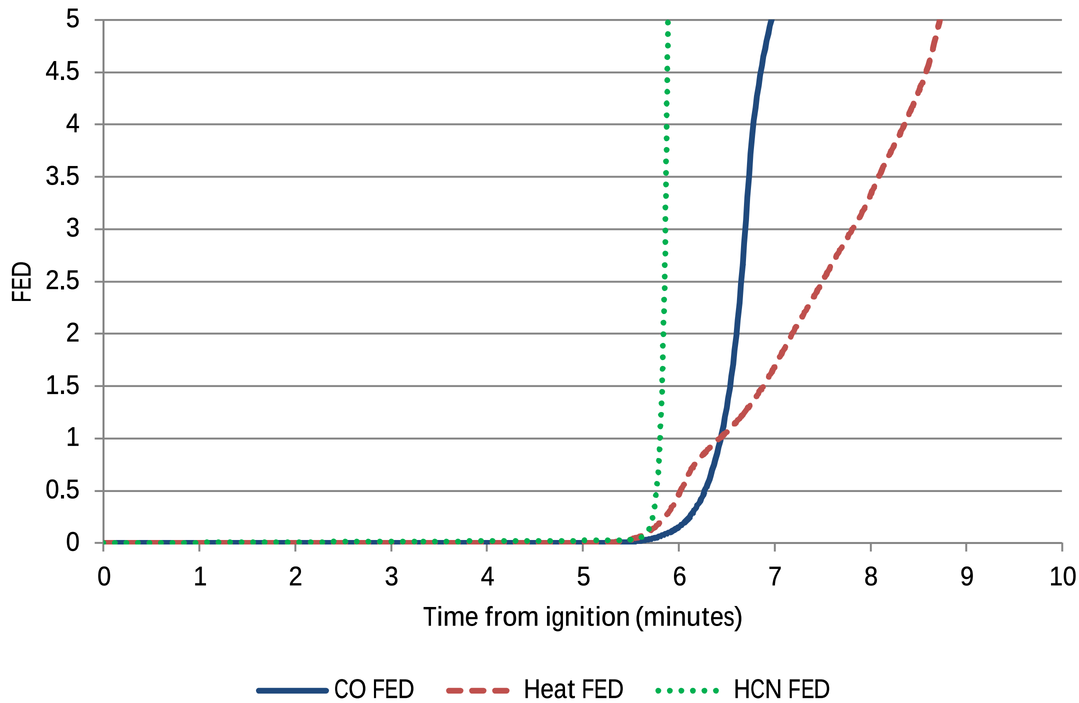


Figure 26 – FED values calculated using ISO 13571 method based upon Maysfield reconstruction data

The manner in which this fire developed means that there was a short time frame between FED values beginning to increase at any significant rate and those values exceeding 1 and 2; less than a minute. However, even within this timeframe it can be seen that the dominant contributor to the overall toxicity is HCN. This is perhaps unsurprising given that the primary fuel sources in this fire were polyurethane foam and rubber crumb. This finding correlates with the relatively high concentrations found in the blood samples from the victims of the fire, even more so when considered in conjunction with the delay in testing blood samples.

2.3. Rosepark Care Home

On 31st January 2004 a fire occurred in the Rosepark Care Home, Glasgow. The fire involved a storage cupboard and resulted in the deaths of fourteen of the residents.

The building was a purpose built two-storey residential care home. The building was built into sloping terrain such that the lower floor was a semi-basement, and in fact the main entrance to the building was on the upper floor. This layout became significant during the course of the incident as the lower floor was sometimes referred to as the lower ground floor and sometimes as the ground floor, whereas the upper floor was either referred to as the ground floor or the first floor.

At the time of the fire, Rosepark Care Home was registered to accommodate up to 43 residents. All of the residents of Rosepark Care Home were, in some way or another, dependent upon assistance from others for the activities of normal daily life. There were 18 residents in the rooms off of corridors 3 and 4 (the corridors affected by fire and smoke during the incident).

The findings of the Fatal Accident Inquiry found that the fire was likely to have started shortly before 04:28 on the 31st January 2004.[134] The fire started in a cupboard which contained shelves, an inner cupboard and an electrical distribution board. On the shelves were a wide variety of items ranging from chamber pots, bowls, cardboard and plastic boxes, through to games for the residents and stationary. The inner cupboard contained toiletries, including aerosols. It was kept locked following a request from the Health Board (to store toiletries securely).[135] The contents of the cupboard are shown in Figure 27.

Figure 27 – Contents of cupboard used for Rosepark reconstruction fires, understood to represent actual contents of cupboard at time of fire. The distribution board (ignition source for the fire) is located in the brown box in the top of the left hand image

The most likely cause of the fire was determined by the Fatal Accident Inquiry as being an earth fault in the electrical distribution board in the cupboard. Specifically, mechanical action between the sharp edge of the earth knockout and the insulation around a live conductor allowed arcing to occur between the conductor and the knockout, heating and igniting first the insulation materials in the distribution board and then the contents of the cupboard.

The layout of the portion of Rosepark Care Home affected by the fire is shown in Figure 28 and a summary of the details of the casualties from the fire is given at Table 13. All of the casualties that died at the scene were located in rooms off of corridor 4 (the corridor in which the storage cupboard where the fire started was situated) and had their doors open (i.e. there were no closed doors separating them from the fire origin). All of the casualties who died some time after being removed from the scene were in rooms that were separated from the fire by one closed door.

Figure 28 – Plan of Rosepark Care Home. Red triangle denotes cupboard where fire started

Deceased (bedroom number)	Status on removal	Corridor	Door	No. doors between room and fire	COHb measure-ment/ estimate*	Finding by FAI (N.B. Soot was not specifically mentioned in FAI report)
Female (10)	Rescued alive	4	Closed	1	43-49	Acute tracheobronchitis due to inhalation of smoke and fire gases. Ischaemic heart disease due to coronary artery atheroma and cardiac amyloidis were potential contributing causes
Male (16)	Deceased	4	Open	0	55	Inhalation of smoke and fire gases
Female (14)	Deceased	4	Open	0	56	Inhalation of smoke and fire gases
Female (17)	Deceased	4	Open	0	58.2	Inhalation of smoke and fire gases
Female (18)	Rescued alive	3	Open	1	44-53	Bronchopneumonia due to the inhalation of smoke and fire gases
Female (12)	Deceased	4	Open	0	80.2	Inhalation of smoke and fire gases
Female (20)	Rescued alive	3	Open	1	42-55	Bronchopneumonia due to inhalation of smoke and fire gases. Chronic obstructive airways disease was a potentially contributing cause of death
Female (11)	Rescued alive	4	Closed	1	43-57	Bronchopneumonia due to hypoxic brain damage and the inhalation of smoke and fire gases
Female (13)	Deceased	4	Open	0	81.8	Inhalation of smoke and fire gases
Female (9)	Deceased	4	Open	0	48	Inhalation of smoke and fire gases
Female (15)	Deceased	4	Open	0	68.3	Inhalation of smoke and fire gases
Female (13)	Deceased	4	Open	0	47.8	Inhalation of smoke and fire gases
Female (9)	Deceased	4	Open	0	63	Inhalation of smoke and fire gases
Female (14)	Deceased	4	Open	0	71.8	Inhalation of smoke and fire gases

* Where a range is given, peak carbon monoxide concentrations were estimated based on calculations using postmortem carbon monoxide concentrations and the time over which treatment was received after victims had been removed from the scene.

Table 13 – Summary of casualty data from Rosepark Care Home fire

2.3.1. Reconstruction and Test Results

During the course of the investigation, a reconstruction and two “alternative scenario” reconstructions were carried out to investigate the conditions that occurred during the incident and how these conditions might have been altered by the presence of, firstly, sprinklers and, secondly, fire resisting doors on all of the bedrooms. The direct reconstruction of the fire is of greatest interest to this work, although the implications arising from the "alternative scenario" reconstructions are discussed as well.

The reconstruction rig was designed to represent three sections of corridor and seventeen bedrooms which were all directly relevant to the incident and the locations of the victims of the incident. The section of corridor where the cupboard was situated can be seen in Figure 29 (before the fire) and Figure 30 (after the fire).

Figure 29 – View of corridor in Rosepark reconstruction rig. The door to the cupboard where the fire started is slightly ajar on the left hand side. One of the thermocouple columns can be seen in the foreground

Figure 30 – View of corridor in Rosepark reconstruction rig corresponding with Figure 29, but after the fire

The rig was instrumented extensively with thermocouples, gas sampling points for both continuous analysis of O_2, CO_2 and CO, and bubblers for discrete analysis of HCN. Thermocouples were installed both in columns (each comprising 5 thermocouples at 0.5m intervals) and at specific locations, in particular on ceilings and at the location where a sleeping resident's nose might have been.

The fire was set in a reconstructed storage cupboard from the incident and allowed to burn itself out after approximately 7 minutes. Fire fighters entered the rig 30.5 minutes after ignition (as they did on the night of the fire) to deal with any hot spots and employ techniques to clear smoke.

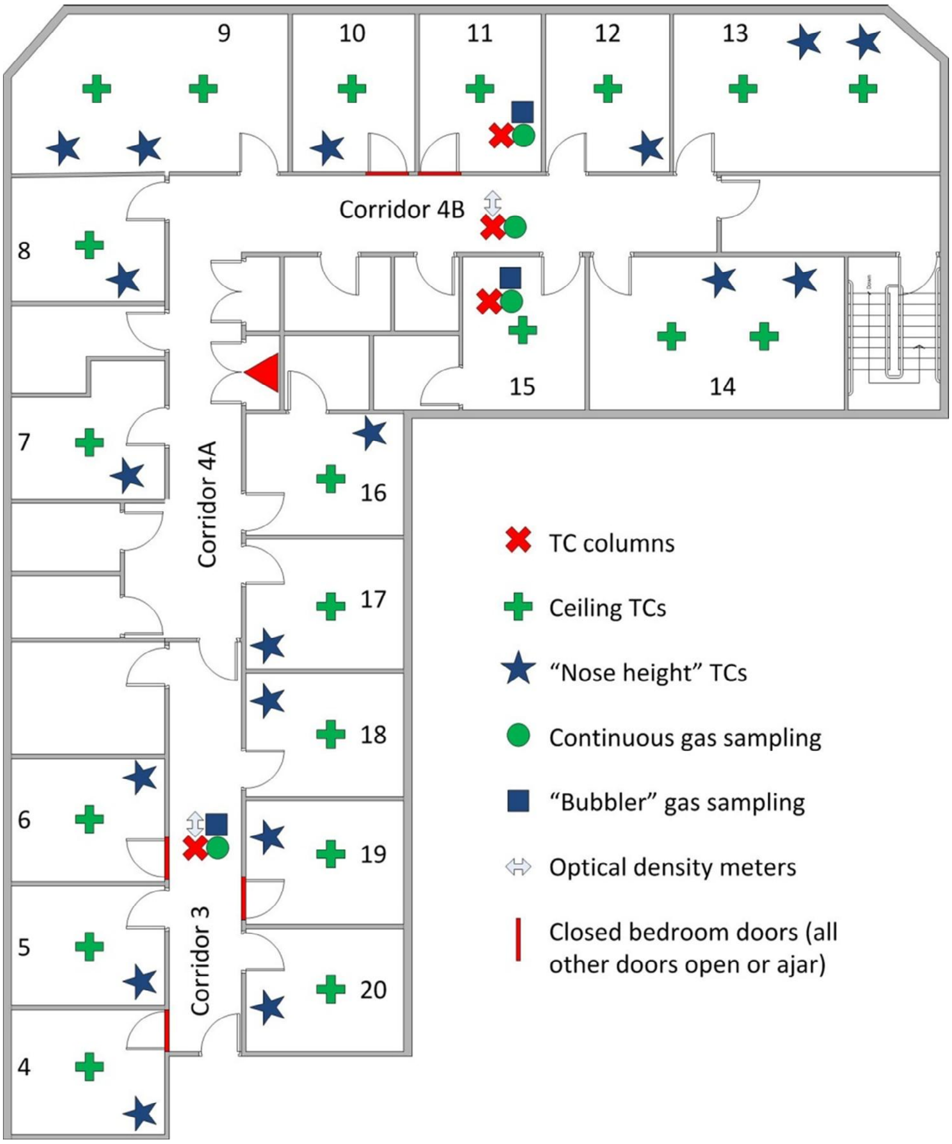


Figure 31 – Plan of instrumentation installed into Rosepark reconstruction rig

The data presented below is for the gas analysis for corridors 4B (Figure 32) and 3 (Figure 33), as well as bedroom 15 (a - door open, Figure 34) and bedroom 11 (b - door closed, Figure 35). This data is considered to be representative of the gas concentrations to which residents in (a) open rooms and (b) closed or corridor 3 rooms were exposed whilst they were in their rooms. It should be noted that the residents in closed or corridor 3 rooms were all carried through the corridor when they were rescued by the Fire and Rescue Service.

Note also that work carried out by Purser as part of this programme of work included the generation of continuous HCN data by establishing a ratio of HCN generation versus oxygen depletion by comparing oxygen data with the periods when discrete samples of HCN were taken.

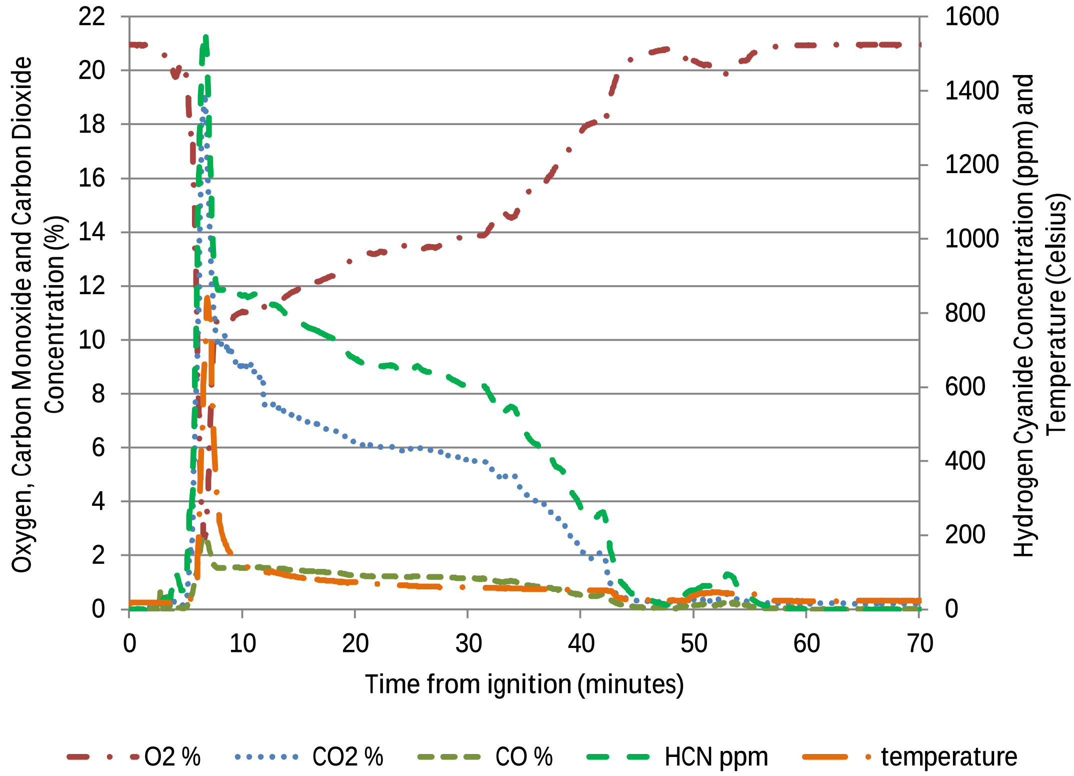


Figure 32 – Gas concentrations measured in Rosepark corridor 4B (fire corridor)

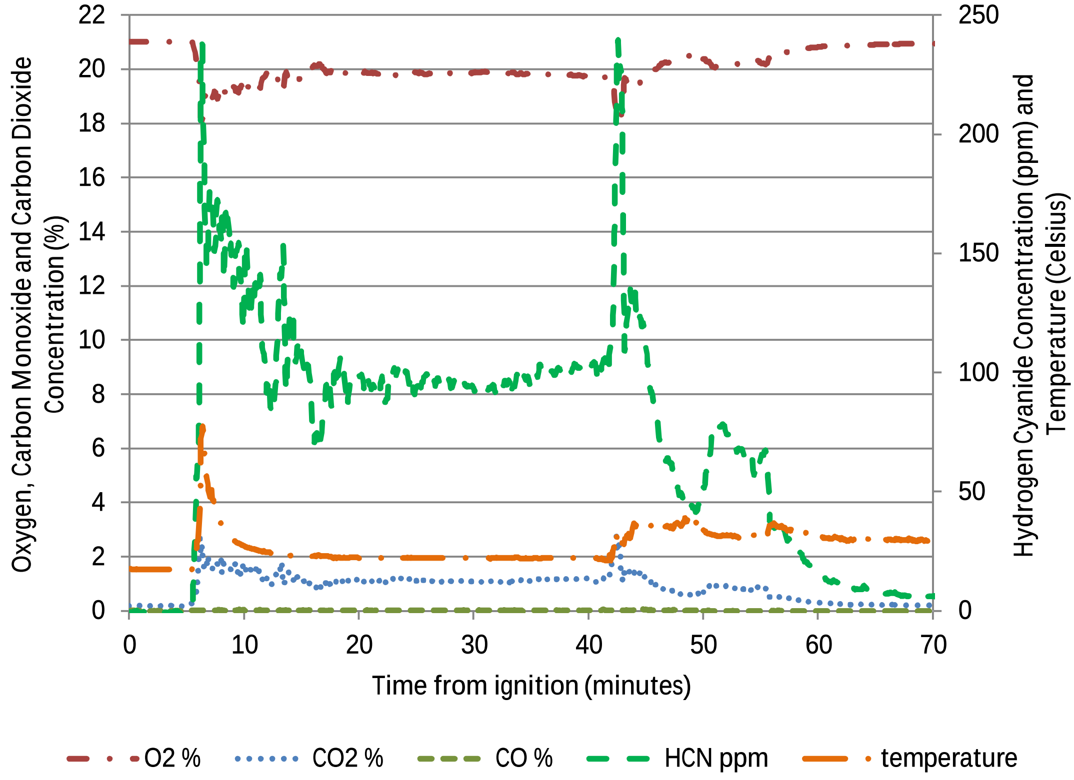


Figure 33 – Gas concentrations measured in Rosepark corridor 3 (corridor off of fire corridor)

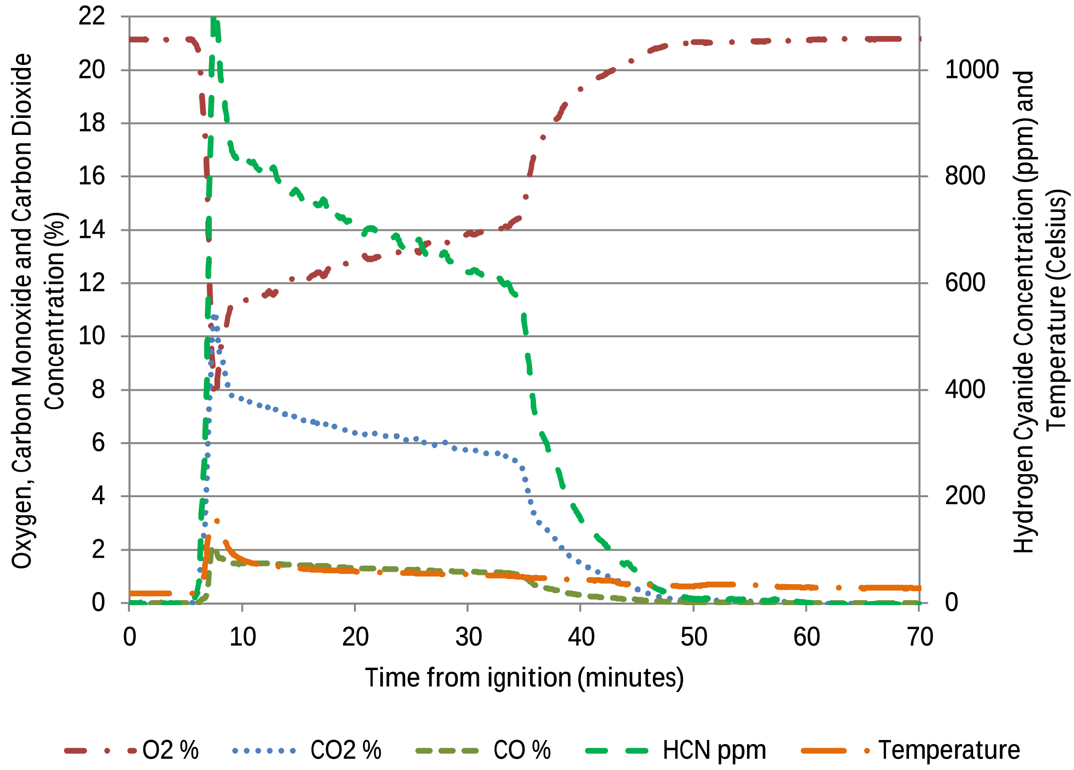


Figure 34 – Gas concentrations measured in Rosepark open room condition

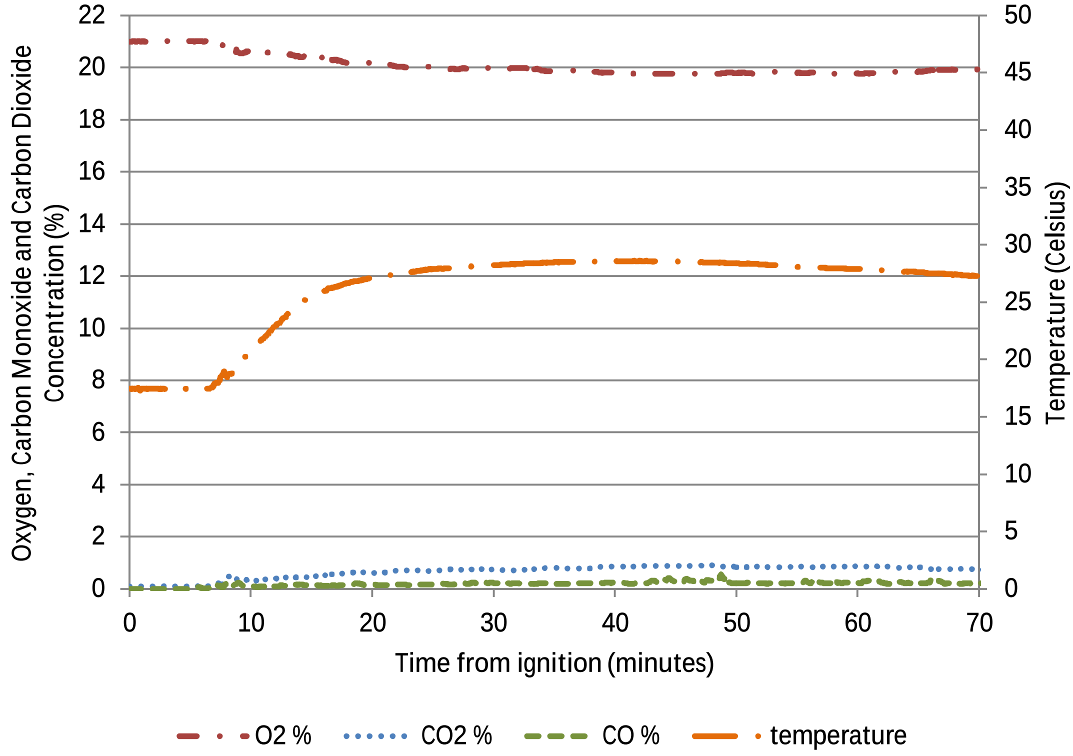


Figure 35 – Gas concentrations measured in Rosepark closed room condition

FED calculations were completed by D Purser during the programme of work carried out by FRS. Note that this work by Purser included the generation of continuous HCN data by establishing a ratio of HCN generation versus oxygen depletion by comparing oxygen data with the periods when discrete samples of HCN were taken. These calculations have been analysed and adapted for the area of focus of this work.

2.3.2. **Sequence of Events Relevant to Analysis**

As mentioned above, the victims of the Rosepark Care Home fire fall into two distinct categories; those which died in their rooms (all of whom had open doors) and those which died some time later (all of whom were separated from the fire by one closed door). Of these two groups, the former can be assumed to have been exposed to the same conditions as those recorded in the open room condition in the reconstruction, whilst the latter must be considered to have been exposed to two environments. At first they were protected from the toxic atmosphere by virtue of the closed doors separating them from the fire, but when they were rescued by the Fire and Rescue Service (opening doors) they became exposed to the conditions in the corridor outside. The details of those who were rescued from their rooms and died later are shown in Table 14.

Deceased	Corridor	Door	COHB measure-ment/ estimate*	Time removed from room	Time from ignition (0426)
Female, room 10	4	Closed	43-49	0540	74 minutes
Female, room 18	3	Open	44-53	0611	105 minutes
Female, room 20	3	Open	42-55	0600	94 minutes
Female, room 11	4	Closed	43-57	0509	43 minutes

Table 14 – Summary of data of residents rescued from Rosepark Care Home fire that died later

2.3.3. **FED Data from Experimental Data**

FED calculations have been carried out for each of the four relevant measuring locations in the Rosepark reconstruction fire. The results of these calculations are shown in Figure 36 to Figure 39.

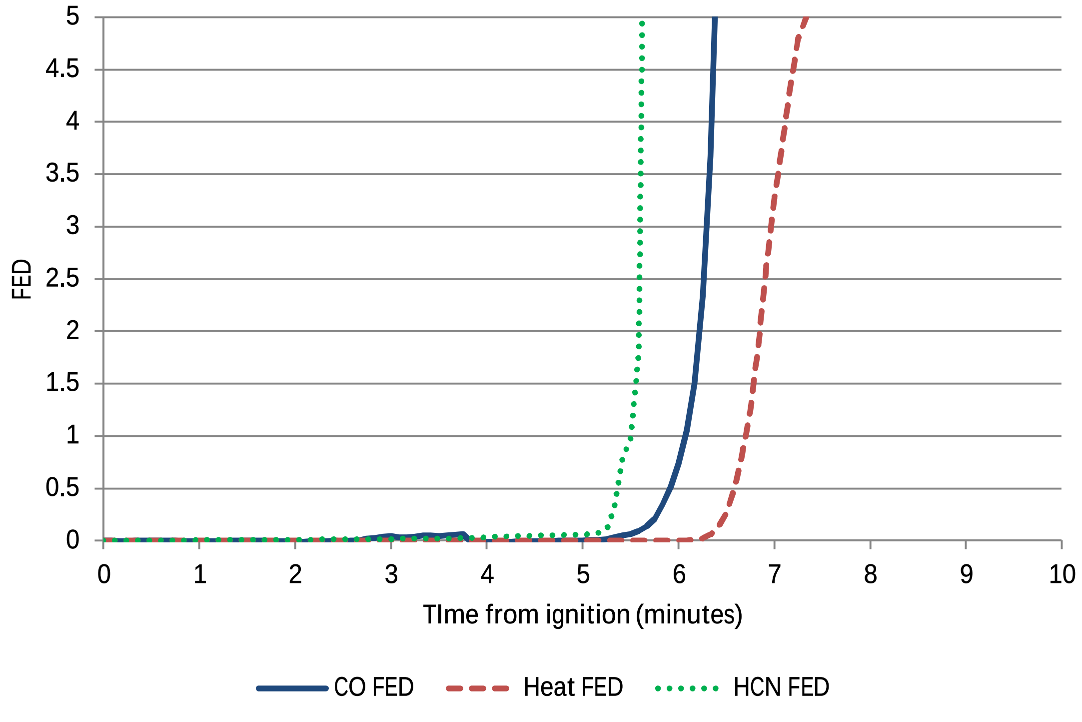


Figure 36 – FED values calculated using ISO 13571 method based upon Rosepark corridor 4B reconstruction data

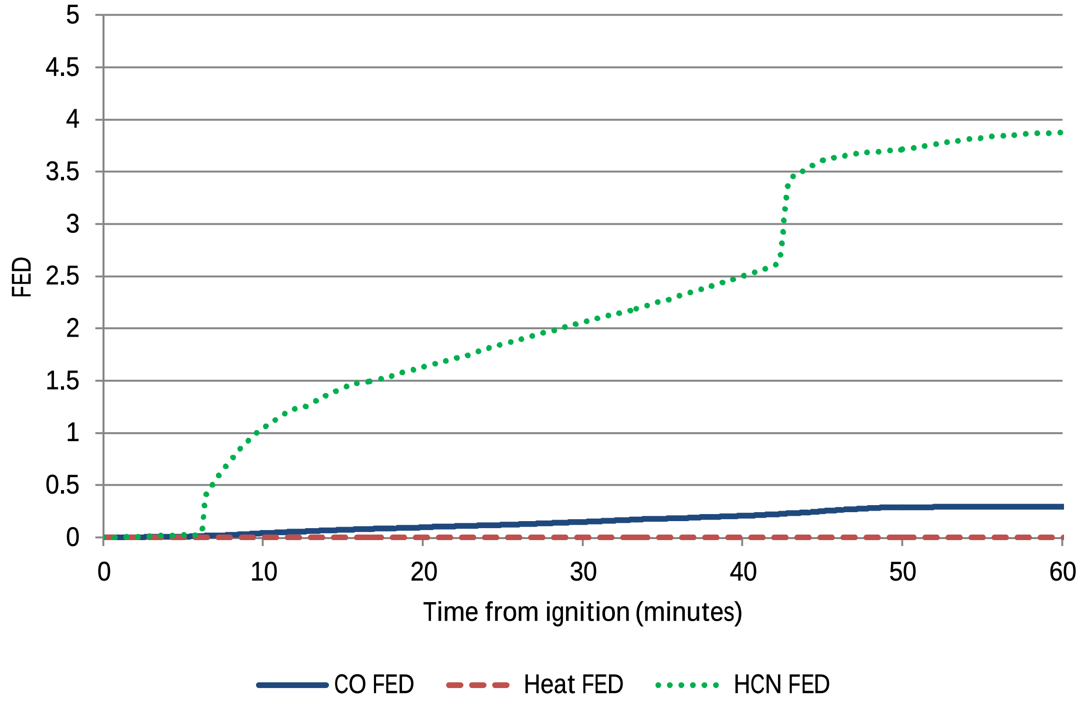


Figure 37 – FED values calculated using ISO 13571 method based upon Rosepark corridor 3 reconstruction data

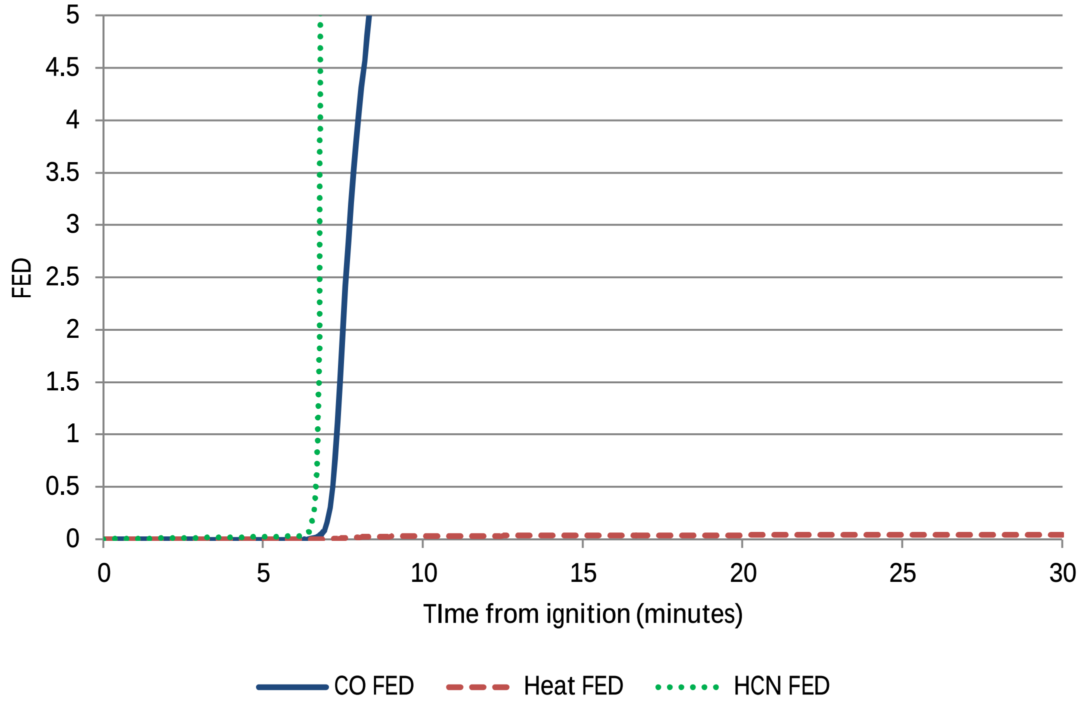


Figure 38 – FED values calculated using ISO 13571 method based upon Rosepark open room reconstruction data

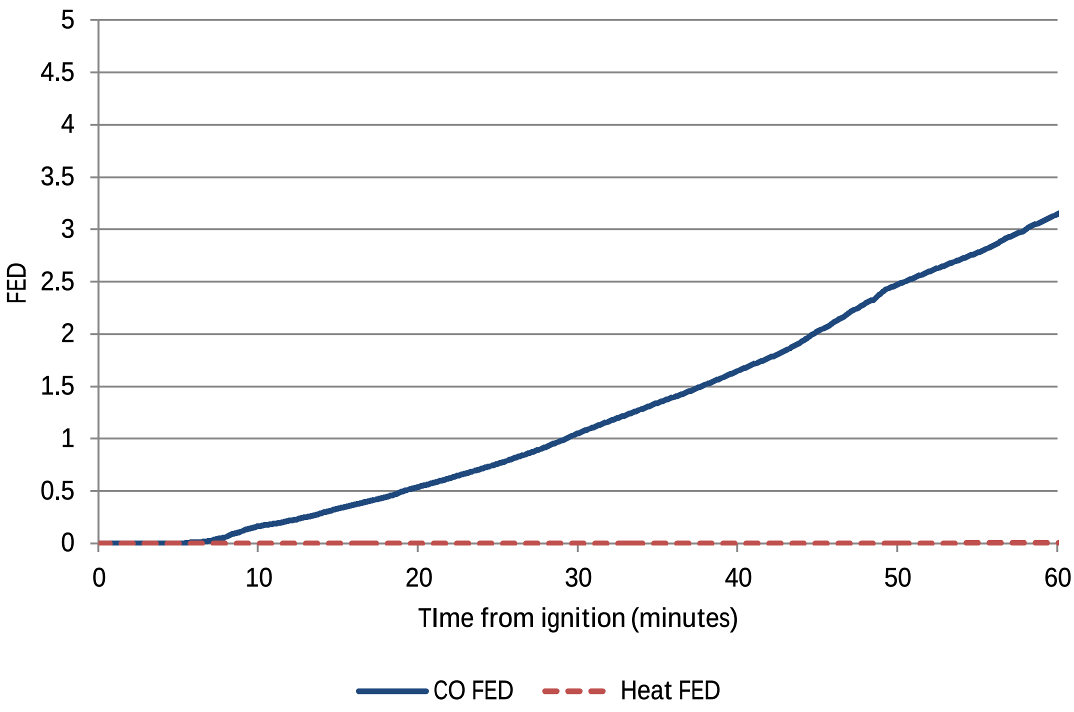


Figure 39 – FED values calculated using ISO 13571 method based upon Rosepark closed room reconstruction data

From the Rosepark data it can be seen that heat only presented a significant hazard in corridor 4B; the corridor in which the fire cupboard was situated. In terms of the hazard from asphyxiant gases, hydrogen cyanide appears to be the dominant contributor to overall toxicity. It is interesting to note that carbon monoxide has a significant impact in both the corridor 4B and open room condition, but that its significance diminishes significantly in corridor 3, whilst the impact of hydrogen cyanide appears to remain significant. No equivalent comparison could be made for the closed room condition as hydrogen cyanide sampling was not carried out here.

The findings of the work carried out by Purser in support of the Fatal Accident Inquiry are consistent with these findings, although further work was also carried out to consider the environments to which each of the victims was exposed as they were moved through the building and various fire atmospheres during the efforts to effect their rescue.

2.4. Harrow Court

In the early hours of Wednesday 2nd February 2005, fire broke out in Flat 85 on the 14th floor of Harrow Court, Silam Road, Stevenage. The fire resulted in the deaths of one of the occupiers of the flat and two fire fighters from Hertfordshire Fire and Rescue Service.[136]

On Tuesday 1st February 2005 at approximately 21:00 the electricity supply ran out in Flat 85. The occupiers did not have any meter cards or credit left, so one of the occupiers (male 1) approached a neighbour who gave him some tea light style candles. Male 1 and the other occupier (female 2) had a number of alcoholic drinks with a friend in their flat until around 23:00hrs, when the friend left and they went to bed.

Two tea lights were lit with a cigarette lighter by male 1 and placed directly onto a portable television in their bedroom. The couple went to sleep at approximately 23:40hrs without extinguishing the tea lights.

The fire was first noticed by one of the occupants of Flat 91 (immediately above Flat 85) at approximately 03:00. Flames were reported to be issuing from the main bedroom window of Flat 85. Around the same time the occupant of Flat 95 on the 16th floor heard a male voice shouting “Get out. Get out”. He subsequently looked out of his lounge window and noticed smoke ‘billowing’ from a lower bathroom window.

Male 1 stated that when he awoke he saw a flame approximately a foot in height from one of the tea lights on top of the television. He believed that the flame was from the tea light placed closest to the wardrobe side. He didn’t wake female 2, but decided to get a dampened tea towel and he went to the lounge, situated at the far end of the flat, to try to find one.

Male 1 stated that after a short period of time he attempted to return to the bedroom, but found he was no longer able, due to heat and smoke discharging from the bedroom. At this time he shouted to female 2, but got no response. He then made his way back to the lounge where he remained until he heard banging on the front door of the flat. In response he shouted “I can’t get to the door – you will have to kick it in”. Male 1 then remembered seeing a fire fighter in the lounge. Male 1 was rescued by HFRS personnel who led him out of the flat. The two fire fighters then entered and continued to search the flat in order to attempt to rescue the second occupier. In doing so, they both fell victim to the fire as did female 2.

During the fire an apparently sudden and unusual event occurred during the fire development which led to a significant change in the tenability conditions inside the flat. The event occurred shortly after the two fire fighters entered the flat. They had been able to successfully rescue one occupant, however a short time later, while attempting to rescue the second occupant; both fire fighters were overcome and died.

From the postmortem analysis, it was found that female 2 died as a result of smoke inhalation whilst the cause of death of both fire fighters was due to their thermal injuries.[137] No further detail is available regarding the toxicology or the specific nature of the causes of death.

2.4.1. **Reconstruction and Test Results**

As part of the investigation experimental trials and computer modelling were carried out to try to get a better understanding of the conditions during the incident.[138] Computer modelling was used to gain insight into the nature of the sudden event and the conditions leading up to it and to provide guidance on the design of the experimental trials. Some measurements of airflow rates and directions were conducted in Harrow Court to verify some of the simulations.[139]

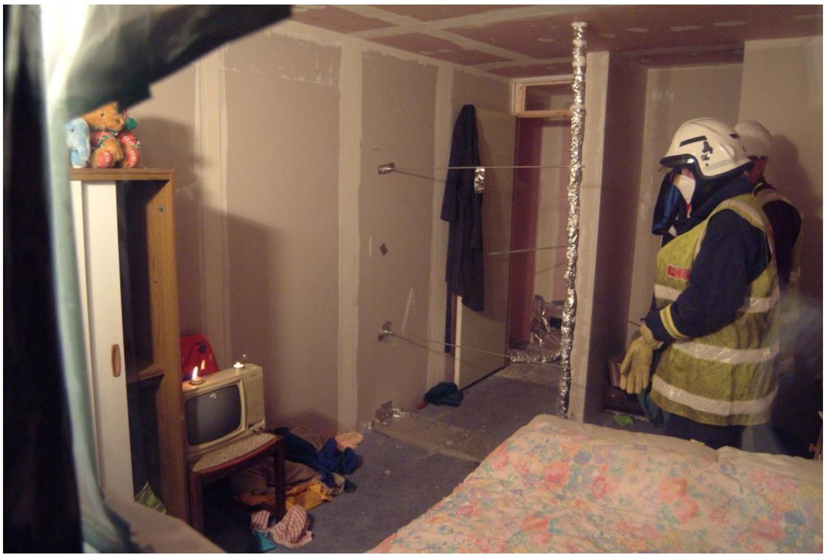


Figure 40 – View of start of reconstruction fire (ignition recreates candle “tea-lights” left on top of television set by occupants). Thermocouple column and gas sampling lines can also be seen[138] (see Appendix A)

Figure 41 – View of outside of reconstruction rig during fire, showing venting out of window and into corridor[138] (see Appendix A)

The data presented here are for the gas concentrations and temperatures measured within the bedroom (where the civilian victims were located, Figure 42 and Figure 43) and the temperature measurements in the corridor (where the fire fighters wearing breathing apparatus were working before they were overcome, Figure 44).

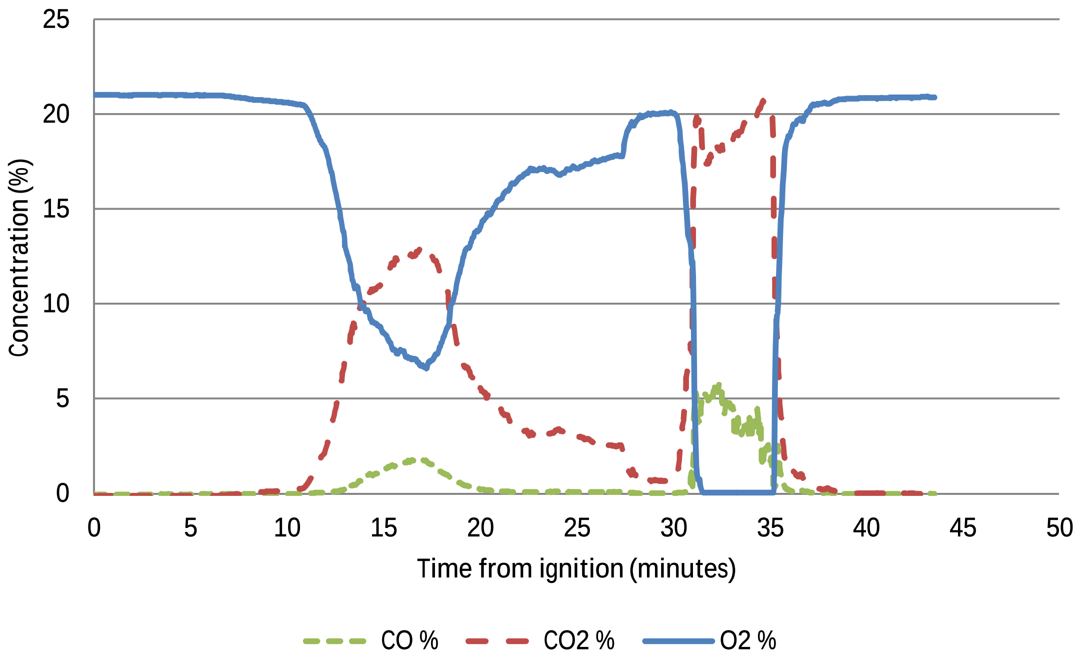


Figure 42 – Gas concentrations measured in reconstruction fire in Harrow Court bedroom, nose height of standing person[138]

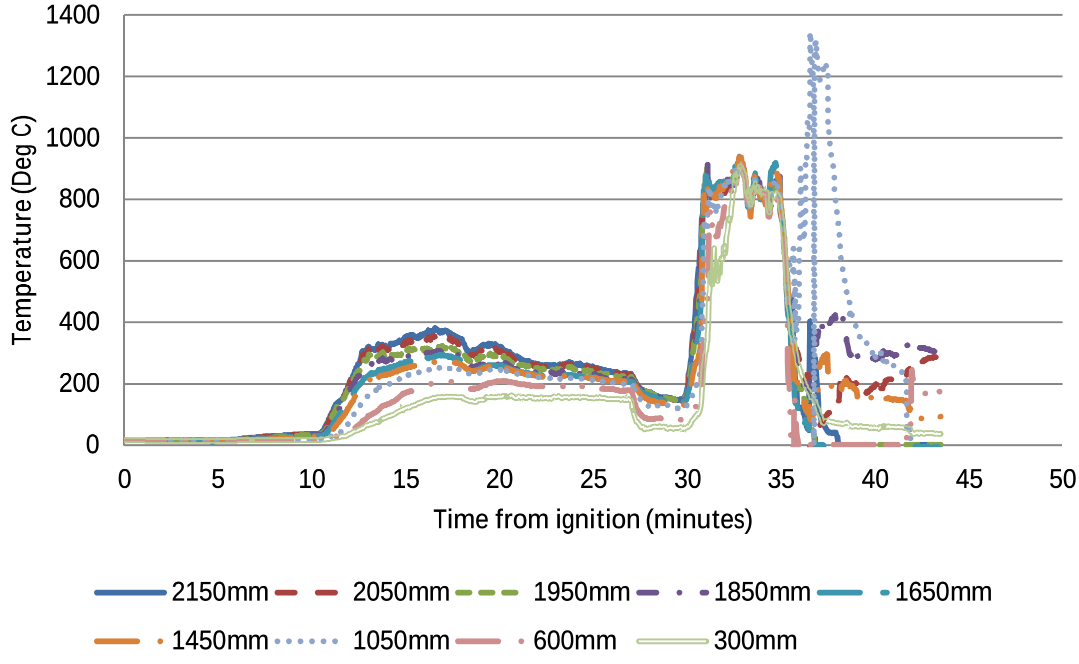


Figure 43 – Temperatures measured in reconstruction fire in Harrow Court bedroom at heights from floor. N.B. The erratic peaks after 35 minutes are due to fire fighting activity[138]

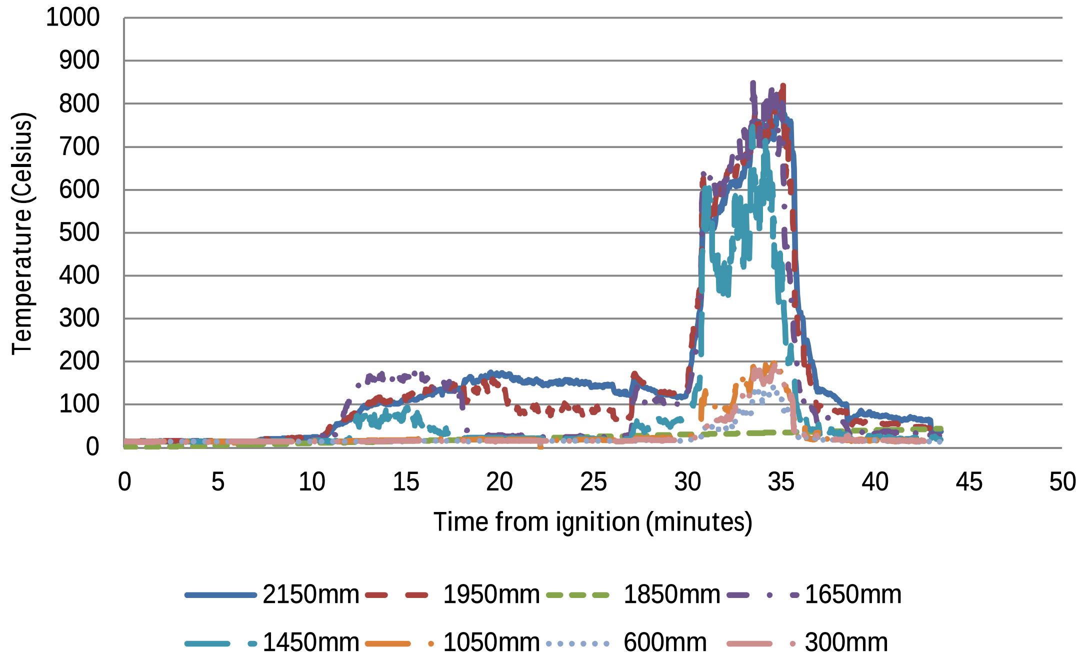


Figure 44 – Temperatures measured in reconstruction fire in Harrow Court corridor at heights from floor[138]

2.4.2. **Sequence of Events Relevant to Analysis**

The Harrow Court fire was initially a relatively typical compartment fire. The fire developed within the room of origin until its size caused it to spread to involve the remainder of the flat. The arrival of the Fire and Rescue Service led to the opening of doors within the common area of the block and this appears to have coincided with the fire causing failure of the windows, allowing the air movements around the high rise block to directly impact upon the development of the fire.

During the fire an apparently sudden and unusual event occurred during the fire development which led to a significant change in the tenability conditions inside the flat. The event occurred shortly after the two fire fighters entered the flat. They had been able to successfully rescue one occupant, however a short time later, while attempting to rescue the second occupant; both fire fighters were overcome and died.

2.4.3. **FED Data from Experimental Data**

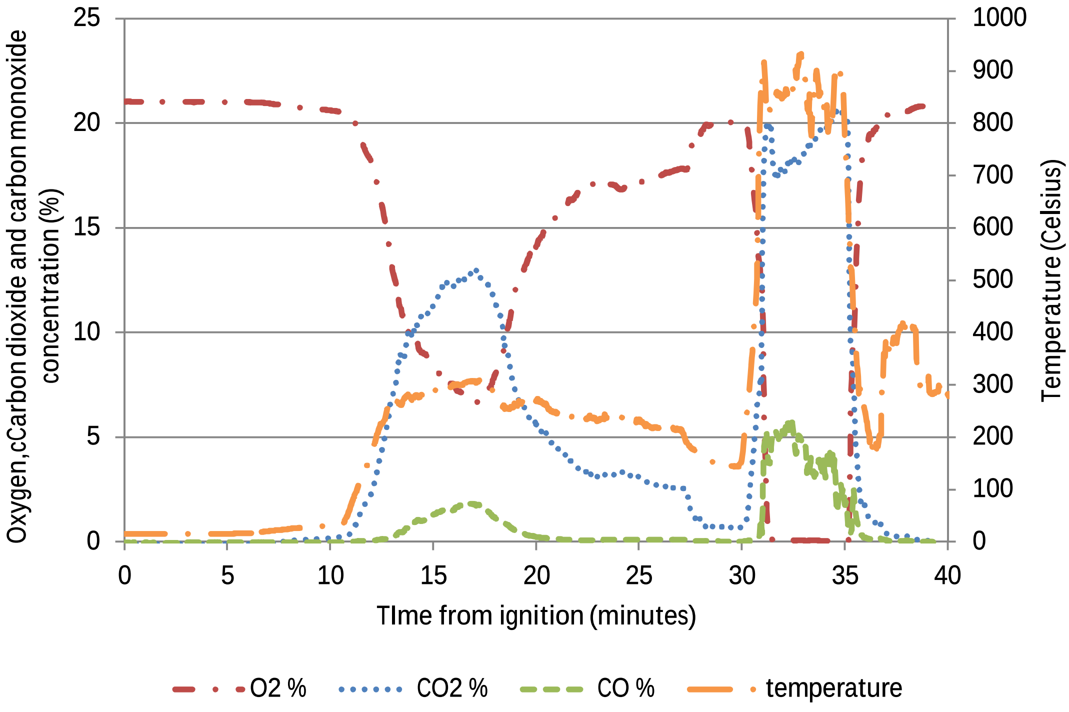


Figure 45 – Data used from Harrow Court reconstruction data standing up measurements for FED calculations

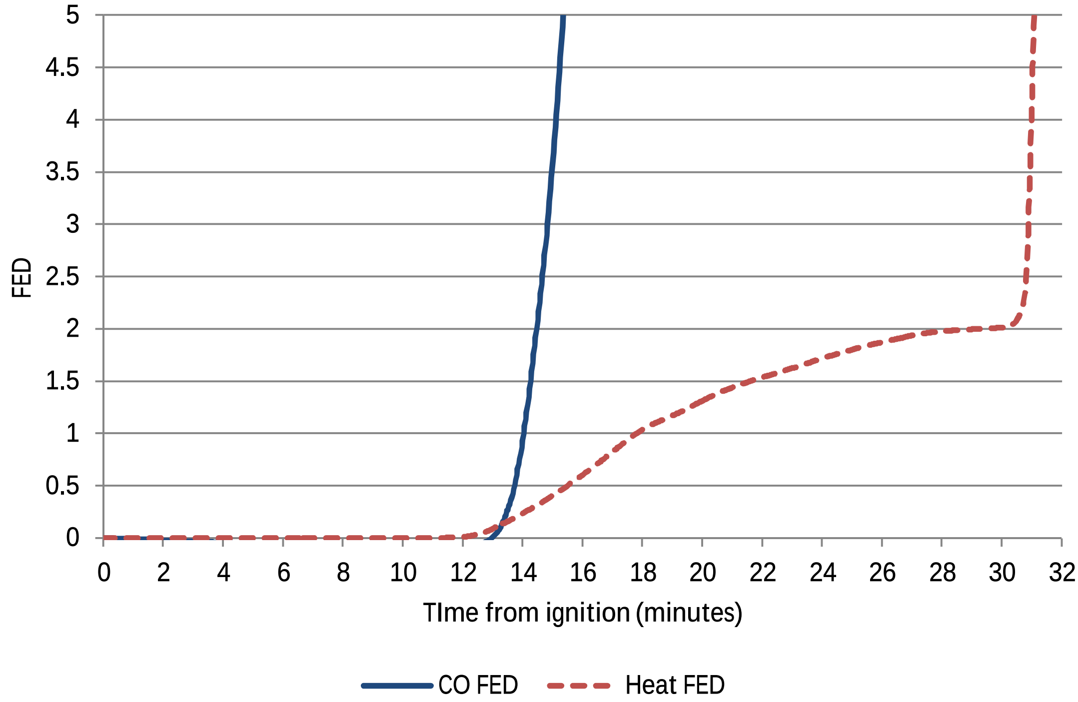


Figure 46 – FED values calculated using ISO 13571 method based upon Harrow Court reconstruction data standing up measurements

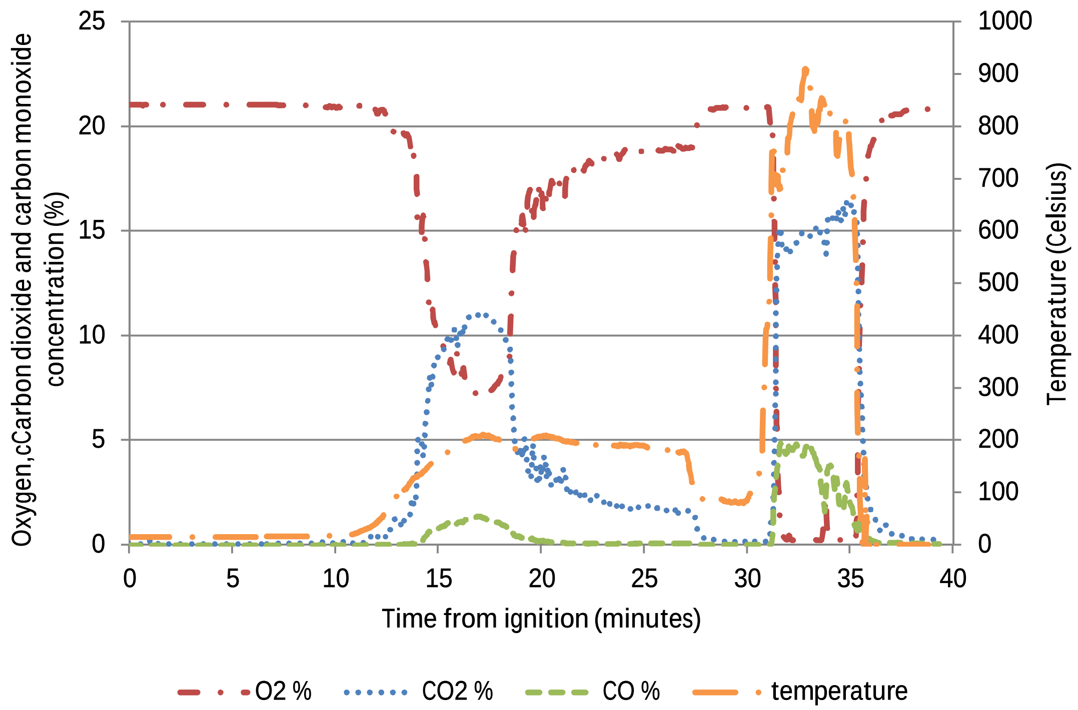


Figure 47 – Data used from Harrow Court reconstruction data lying down measurements for FED calculations

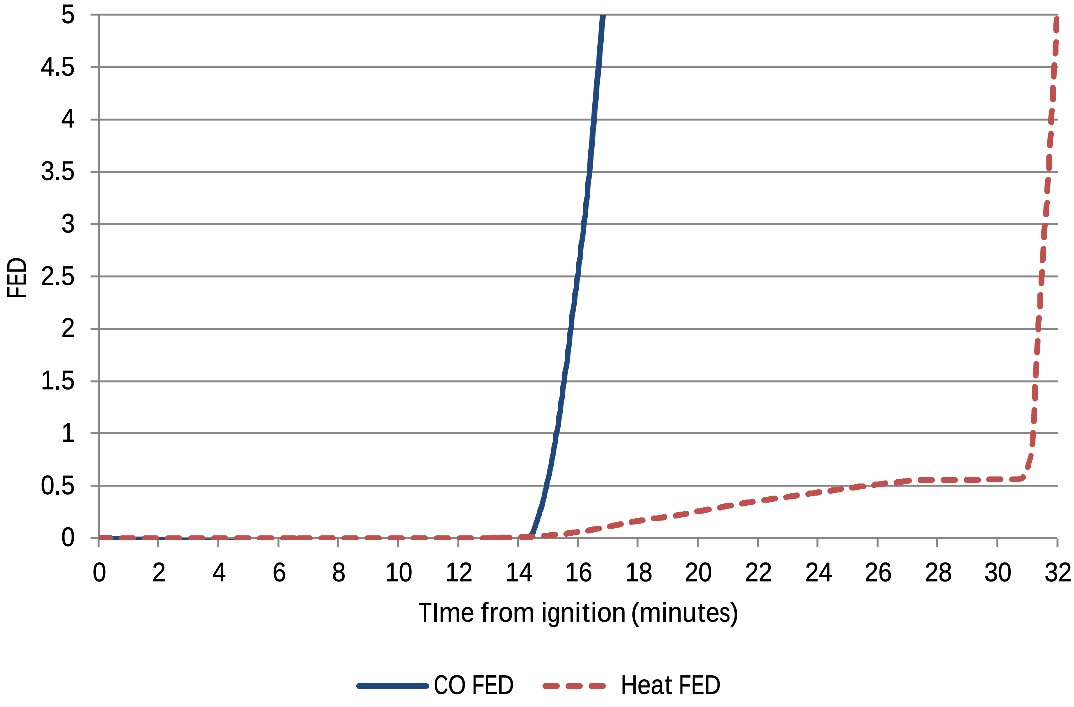


Figure 48 – FED values calculated using ISO 13571 method based upon Harrow Court reconstruction data lying down measurements

The hazard analysis for this incident shows clearly the two key points during the course of the incident; the point at which conditions become untenable for the occupants of the flat due to the fire gases, and the point at which conditions become untenable for the fire fighters due to the sudden increase in temperature. Given the nature of this fire, in particular the mixture of fuel materials for the fire afforded by the domestic setting (wood, foams, moulded and extruded plastics, fabrics, etc.), it would be extremely difficult to assign the properties of any one of these items to the way in which conditions developed. Indeed, it is far more likely that the prevailing wind movements and the overall fire development within the compartment were responsible, therefore thermal insulation by the structure and global equivalence ratio governed by the availability of air through openings into the compartment were probably the deciding features here.

3. RECREATED BUILDING FIRES

The reconstructions of the fires at Lakanal House and Wealmoor Atherstone have been carried out by the author.

3.1. Lakanal

On 3rd July 2009, a fire broke out in Lakanal, a 16 storey block of maisonettes constructed between 1955 and 1960. The fire spread extensively throughout the building and claimed the lives of six people. Lakanal contains 98 two-storey maisonettes; 14 per two-storey level. There are 14 accommodation storeys, an undercroft at ground level and a plant level on the uppermost floor. The maisonettes (hereafter referred to as flats) interlock in a scissor arrangement across the block, with the lower floor of each flat on one side of the block (and common access corridor) and the upper floor of each flat spanning the width of the block. The layout of interlocking flats in a two-storey level is given in Figure 49.[140]

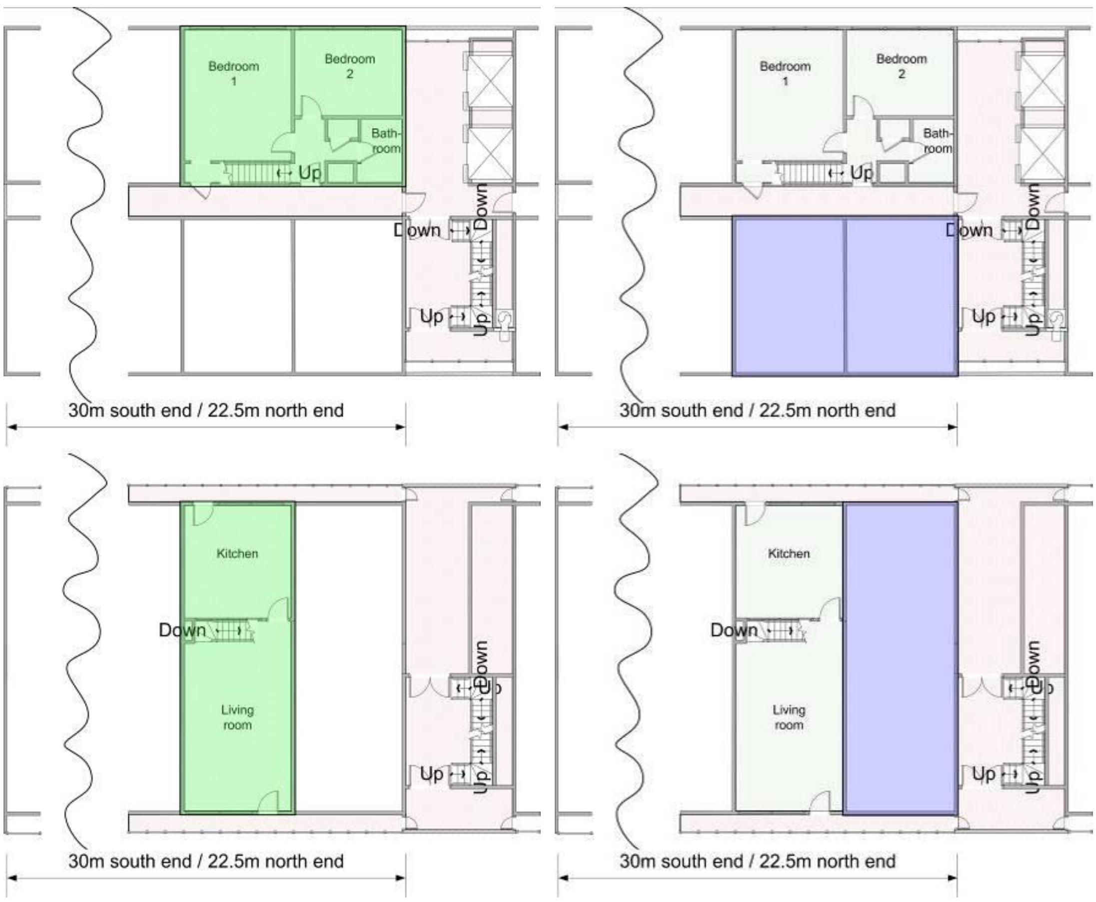


Figure 49 – Plan view diagram showing interlocking of flats and corridor[140]

The fire started in Flat 65 on the 9th and 10th floors. The fire spread and involved Flat 79 directly above, on the 11th and 12th floors, and subsequently the communal corridor on the 11th floor. Fire also spread to Flat 37 on the 5th floor and Flat 53 on the 7th floor. Six lives were lost during the fire; of these one was in the upper floor of Flat 79 and five were in the bathroom of Flat 81; the flat adjacent to Flat 79. The positions of these flats and overview of the extent of the fire spread in Lakanal can be seen in Figure 50.

Figure 50 – West face of Lakanal, showing locations of flats involved in the fire[140]

A programme of work was developed so that computer modelling could examine fire development and spread of fire and smoke throughout the entire geometry of Lakanal whilst taking into account prevailing environmental conditions (e.g. ambient temperature, wind speed and direction) as were present during the incident. Computer modelling was necessary to deal with an incident of this scale, but was supported and validated against a partial full-scale reconstruction of the fire in Flat 79. An assumption that a real fire based upon fuel loading and layout is consistent with that of Lakanal.

3.1.1. **Sequence of Events - Findings from Scene Investigation**

Fire broke out in a television set in bedroom 1 of Flat 65, situated on the 9th floor of Lakanal House. There were 2 individuals in the maisonette; a woman and a baby, both situated in the living room. The woman was reported by LFB to have been alerted to the fire by the smoke alarm, situated on the ceiling above the staircase. She is said to have found a flaming fire situated in the corner of bedroom 1 furthest away from the foot of the staircase. She is then reported to have attempted to fight the fire herself before deciding to evacuate herself (and the child) via the upper floor balcony.

Bedroom 1 appears to have contained a high fuel load. In addition to the television, there was a large bunk bed (double width lower level, single upper level) and a single bed, plus lightweight canvas furniture filled with clothing, Figure 51.

Figure 51 – Bedroom 1 of Flat 65, showing bunk bed and single bed [140]

The alarm was raised to other residents verbally. Fire spread through the interior of the maisonette, into bedroom 2 and up the staircase to the upper floor, eventually fully involving both floors within the maisonette (i.e. floors 9 and 10). This was evidenced by the level of charring to wooden surfaces (particularly staircase), the complete destruction of internal walls and that concrete and blockwork walls have been stripped bare by the fire.

The fire broke out of the windows, with flames extending up the building façade on both east and west faces, and back in through the window assembly of the flat above on the west face; Flat 79 on the 11th floor.

Flat 79 was occupied by a fashion student. As a result, the fire load in bedroom 1 appears to have been exceptionally high. Fashion magazines and catalogues appear to have been stored here, along with stocks of textiles (fabrics and completed garments) and a set of sewing machines. The lower floor of Flat 79 showed extensive fire damage including complete destruction of stairs and internal walls, as well as spalling of concrete which has exposed reinforcing bars. However, the upper floor of Flat 79 suffered comparatively little damage, with many of the soft furnishings still present, albeit charred. This is believed to be due to windows and doors (all closed) on this floor having remained intact until LFB intervention, producing highly vitiated conditions. The occupant of Flat 79 was overcome by smoke in the living room.

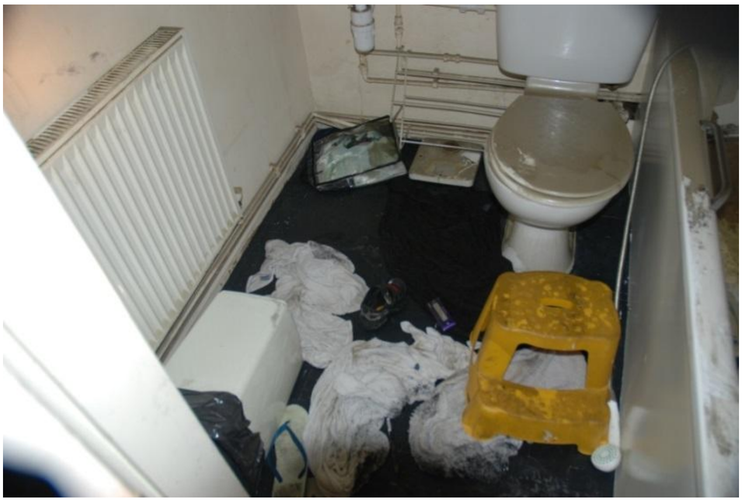
The fire at some point burnt through the stair structure and entered the cavity above the suspended ceiling in the corridor outside Flat 79 (11^{th} floor). The ceramic board detail where the staircase passed through the cavity would not have hindered fire spread from the maisonette into the cavity. This is because the detail was fitted to the staircase itself, so would have collapsed as soon as the staircase was sufficiently charred by the fire. The fire spread in the cavity proceeded both along the corridor away from the lobby, and over the lobby into the cavity above the far (south) corridor. This was because there was no fire stopping or cavity barriers in this cavity along the entire length of the building and the cavity contained a significant quantity of combustible material, as described earlier. The fire in the corridor ceiling cavity also allowed smoke to spread, to varying degrees, into all the other maisonettes on this level. The fire in the lower floor of Flat 79 at some point also burnt through the front door into the corridor.

Following the failure of the front door to Flat 79, fire spread into the north corridor and is believed to have involved both the suspended ceiling and the vinyl floor tiles. Fire appears to have then been pulled/pushed through the length of the corridor on the 11^{th} floor by the prevailing wind passing through fixed vents, and appears to have caused flaming throughout the full height of corridor, evidenced by charring to flat doors (discussed later). The fire is known to have fully involved the corridor by 17:22:15, as seen on Figure 52.

Figure 52 – Smoke emitting from the end of the 11^{th} floor corridor at 17:22:15 during the incident[140]

Flat 81, where the five other occupants were found, was affected by the fire, and more significantly by smoke. Both doors (front and escape) to Flat 81 remained in situ throughout the incident. However they were significantly charred throughout their entire height. The fire spread into the flat through the detail under the stairs. The failure of this detail is likely to have been affected by both the fire within the cavity above the suspended ceiling and the mechanical action of the collapse of this ceiling. The fire burnt through the maisonette staircase, causing some fire damage to the surrounding area. This spread, combined with small points around the doors where the fire had burnt completely through, would have allowed smoke to fill the flat. The five occupants (initially nine, discussed in more detail later) were in the bathroom to this flat. Additional smoke spread into the bathroom later into the incident as a result of fire spread down to the 7^{th} floor. Table 15 summarises the fire and smoke damage in the flat based on post fire photographs and site visits.

Room/space	Evidence of fire	Reference
Bedroom 1	Window cracked in corner Slight smoke staining near trickle vent	 DSC_0102 taken by Whitmore (LFB photographer, see Appendix C)[140]
Bedroom 2	No smoke staining or smoke deposits on surfaces	 DSC_0093 taken by Whitmore (LFB photographer, see Appendix C)[140]

Bathroom	Precipitated smoke on horizontal surfaces Smoke stains on ceiling around cupboard and door frame Smoke in ventilation duct	 DSC_0039 taken by Whitmore (LFB photographer, see Appendix C)[140]  DSC_0040 taken by Whitmore (LFB photographer, see Appendix C)[140]
Hall	Fire damage to top edge of front door, top of door panel	 DSC_0104 taken by Whitmore (LFB photographer, see Appendix C)[140]

<table>
<tr><td>Stairs</td><td>Burnt through at after turn, heat damage in stair well, glass panel to kitchen cracked</td><td>
DSC_6828 taken by D Crowder[140]

DSC_6829 taken by D Crowder[140]</td></tr>
<tr><td>Living area</td><td>Smoke staining at ceiling and walls precipitated soot on horizontal surfaces. Tarry deposits on glass surfaces</td><td>
DSC_6830 taken by D Crowder[140]</td></tr>
</table>

Table 15 – Fire and smoke damage throughout Flat 81

All the flats have a number of service openings between the corridor and the flat in the area between the front door and the bathroom. This space originally contained part of a hot air heating system. In Flat 81 this had been replaced by a hot water tank with immersion heater. At ceiling level, there are a number of openings where services (current and disconnected) pass though into the void above the corridor. Figure 53 shows a schematic view of the wall between the flat and the corridor as seen from inside the flat and the bathroom/hall ceiling, including areas of smoke staining and fire damage.

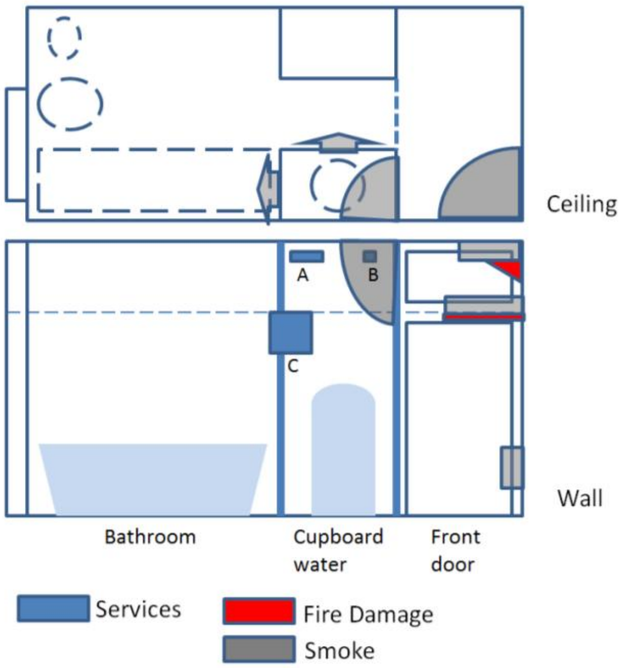


Figure 53 – Flat 81 Bathroom and hall services and smoke staining[140]

There are three areas shown on Figure 53 where services pass through the wall between the flat and the corridor. At location "A" five copper pipes pass through the wall (see Figure 54). The space around the pipes was packed with mineral wool on the flat side and showed no signs of smoke penetration.

Figure 54 – Copper pipes passing through wall at location A (MPS Photo VF10027, see Appendix B)[140]

At location "B" two unused pipes passed through the wall, these are for a disused system and terminate close to the wall inside the water tank cupboard. The inner plasterboard sheet of the wall between the cupboard and hall is broken in the top corner near location "B" and shows some of the heaviest smoke staining in the bathroom area (see Figure 55).

Figure 55 – Disused pipes passing through wall at location B (DSC_0010 (cropped) taken by Whitmore LFB photographer, see Appendix C)[140]

At location "C" there was an opening about 150mm square that had been used for part of an old heating system. On the flat side this was filled with paper (see Figure 56) and partly covered by the bathroom tiles, in the corridor the gap had been plastered over and excavation showed the space was filled with a honeycomb material (see Figure 57). There were no traces of smoke having entered the bathroom at this location.

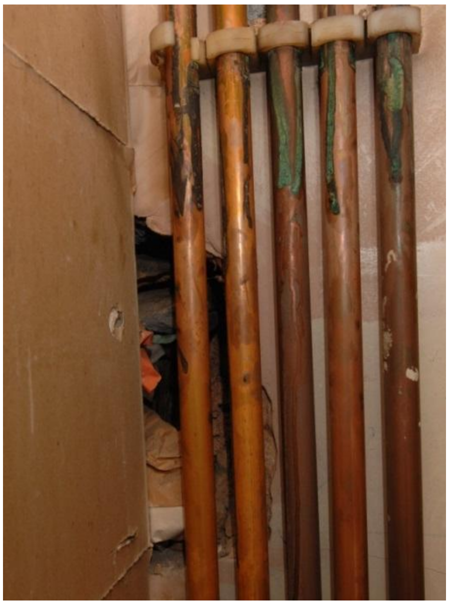


Figure 56 – Flat side of filled disused ventilation opening at location C (MPS Photo VF10030, see Appendix B)[140]

Figure 57 – Corridor side of filled disused ventilation opening at location C (MPS Photo VF10016, see Appendix B)[140]

The pipes at locations "A" and "B" can been seen from the corridor in Figure 58. At "A" the gaps seem to have been stopped with a plastic material that has melted and/or burnt (see Figure 59). The pipes at B had been lagged with mineral wool held securely in place by chicken wire.

Figure 58 – Corridor side of pipe penetration points at locations A and B (MPS Photo VF10018, see Appendix B)[140]

Figure 59 – Close-up of corridor side of pipe penetration point at location A (DSC_0114 (cropped) taken by Whitmore LFB photographer, see Appendix C)[140]

Figure 60 shows a gap between the doorframe and the blockwork wall in the corridor near location "B". This would provide a path for smoke into the cavity of the stud wall between the bathroom cupboard and the hall and thereby into the bathroom. This appears to be the principal route for smoke entering the bathroom after the bathroom ventilation grille had been sealed.

Figure 60 – Close-up of corridor side of pipe penetration point at location B showing gaps in brickwork above pipe (MPS Photo VF10020, see Appendix B)[140]

Fire damage to the north corridor on the 11th floor indicates full involvement from floor to ceiling, evidenced by the consistent depth of char to doors throughout the height of the corridor. Panels above the front doors on the 11th floor were all significantly charred. However, apart from Flat 79, all of these panels remained in place (albeit with some small points of burn through on Flat 81, described above).

Falling burning debris from Flats 79 and 65 (most probably from both the window façade assemblies and the contents of Flat 79, although this has not been possible to ascertain), ignited materials in Flats 37 and 53, located on the 5th and 7th floors respectively. It has not been possible to determine which source of falling debris was responsible for each Flat that was ignited.

Photographs and videos taken by eyewitnesses indicate that the fires in Flats 37 and 53 started shortly before 16:49. Ignition is attributed to burning debris falling from Flats 65 and 79 above. These flats both had windows opened in the swing position.

In Flat 37 the fire damage was confined to bedroom 2, as the bedroom door appears to have been closed and the panel above the door was intact throughout the fire. There was some heat and smoke damage to other rooms in the flat. The doors and windows on the upper level of Flat 37 appear to have been closed during the fire.

In Flat 53 there was fire damage on the lower level (bedroom 1, bedroom 2, the hall and bathroom). The partition wall between bedroom 1 and the stairs had partly burnt through. There was heat damage on the upper level, the glass in the partition between the living room and kitchen had broken and some internal panes of the window glazing had broken. The windows and doors in the living room were closed, but the kitchen windows were open. The fires in Flats 37 and 53 were controlled by the Fire Brigade. However smoke from these flats spread internally in the building either through the common access corridor or through ventilation and service ducts.

The fire in Flat 37 (5^{th} floor), when treated in isolation, looks like a typical flat fire. The fire did not unduly spread back out of the Flat to affect any other areas, other than typical smoke spread.

The fire in Flat 53 (7^{th} floor) was also reasonably typical of a normal flat fire. However it was connected to Flat 81 (as well as 11 on the 1^{st} floor, 25 on the 3^{rd} floor, 39 on the 5^{th} floor, 67 on the 9^{th} floor and 95 on the 13^{th} floor) via the extract ventilation riser from the bathroom. The five occupants in the bathroom of Flat 81 had at one stage reported to a 999 operator that smoke was beginning to enter the bathroom via the extract vent. One of these people left the bathroom to find a magazine and some parcel tape to block up the vent. Inspection of this magazine showed a significant build-up of soot from the vent and some possible scorching. The time taken for the person to find the magazine and tape would have allowed more smoke to enter the bathroom, both through the vent and each time the door was opened, deteriorating the conditions in the bathroom and the survivability.

3.1.2. **Victim Postmortem**

Location where found	Gender	Age	Respiratory examination	Blood COHb %	Lactate	Burns to skin
Flat 79 living room	Female	31	Erythematous trachea, sooting of 2^{nd} & 3^{rd} bronchi, pulmonary oedema	27		76%
Flat 81 bathroom	Female	26	Erythematous trachea, sooting below vocal chords, pulmonary oedema	51		0

Location where found	Gender	Age	Respiratory examination	Blood COHb %	Lactate	Burns to skin
Flat 81 bathroom	Male	3	Erythematous trachea, sooting below vocal chords, pulmonary oedema	23.8		0
Flat 81 bathroom	Female	6	Erythematous trachea, sooting below vocal chords, pulmonary oedema	71		0
Flat 81 bathroom	Female	34	Erythematous trachea, sooting of 1st bronchi, pulmonary oedema	49		0
Flat 81 bathroom	Female	3 weeks	Erythematous trachea, sooting below vocal chords, pulmonary oedema	41	22	0

Table 16 – Details of victims including toxicology and burns[141]

The details for the adult fatalities appear to be consistent with the current tenability limit figures (see chapter 1.3.3). The COHb figure for the male infant appears to be low, but given that there does not appear to have been any opportunity for this victim to breathe an atmosphere different to the other four in Flat 81 (i.e. become exposed to cyanide or other toxicants), this is likely to be a result of age and/or some other physiological factor.

3.1.3. **Reconstruction Setup**

The rig was, as far as possible, to replicate bedroom 1, the lobby and stairs of one of the maisonettes in Lakanal House (Flat 79), as well as a section of the adjacent communal corridor of Lakanal House. The extent of the rig was determined by the physical size of the Burn Hall and its capacity for collection and measurement of fire gases (calorimetry), whilst needing to incorporate sufficient features from Lakanal House in order to meet the objectives of the programme of work. The design of the rig can be seen in Figure 61 and Figure 62.

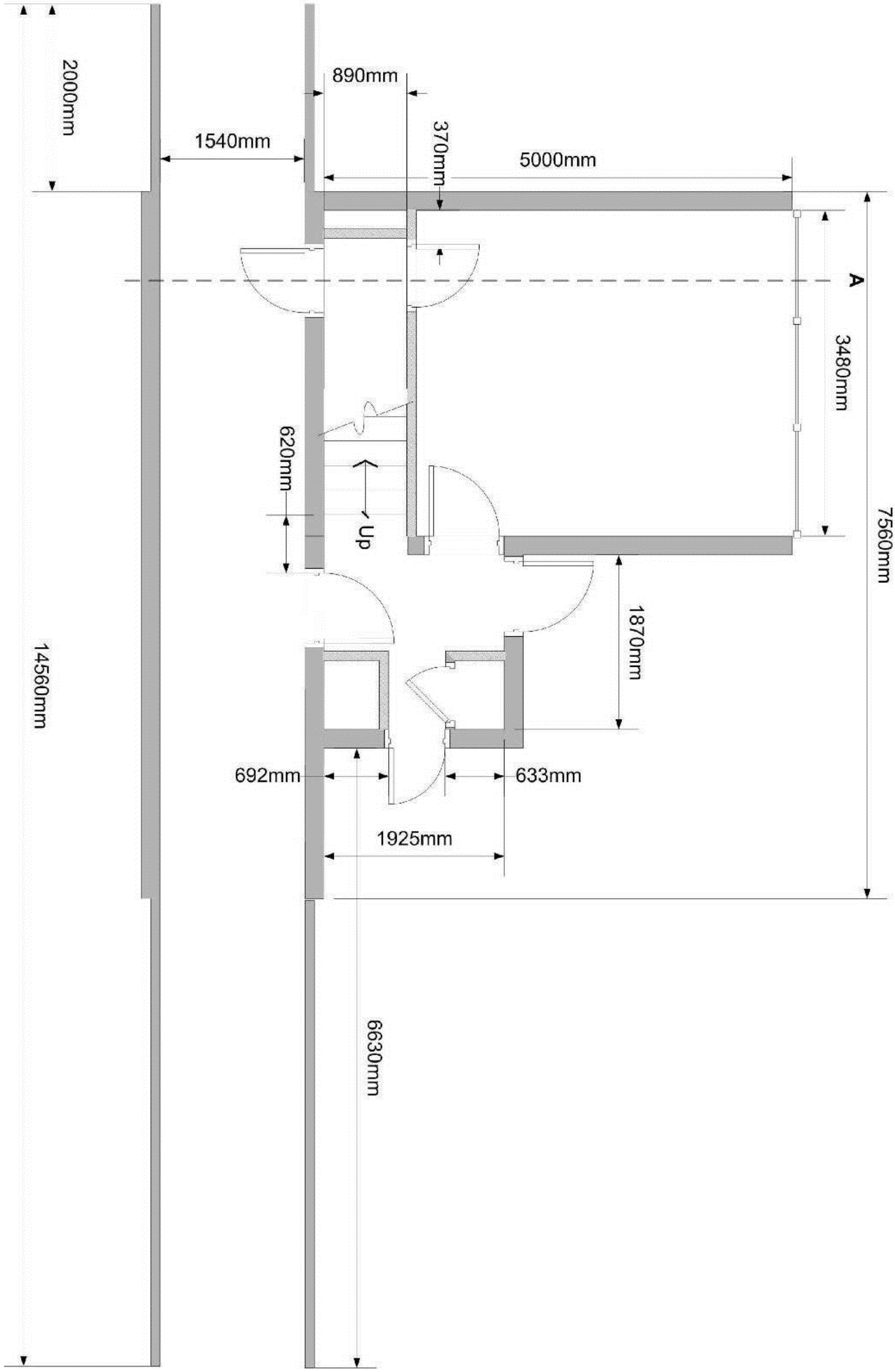


Figure 61 – Ground floor plan of the reconstruction rig[140]

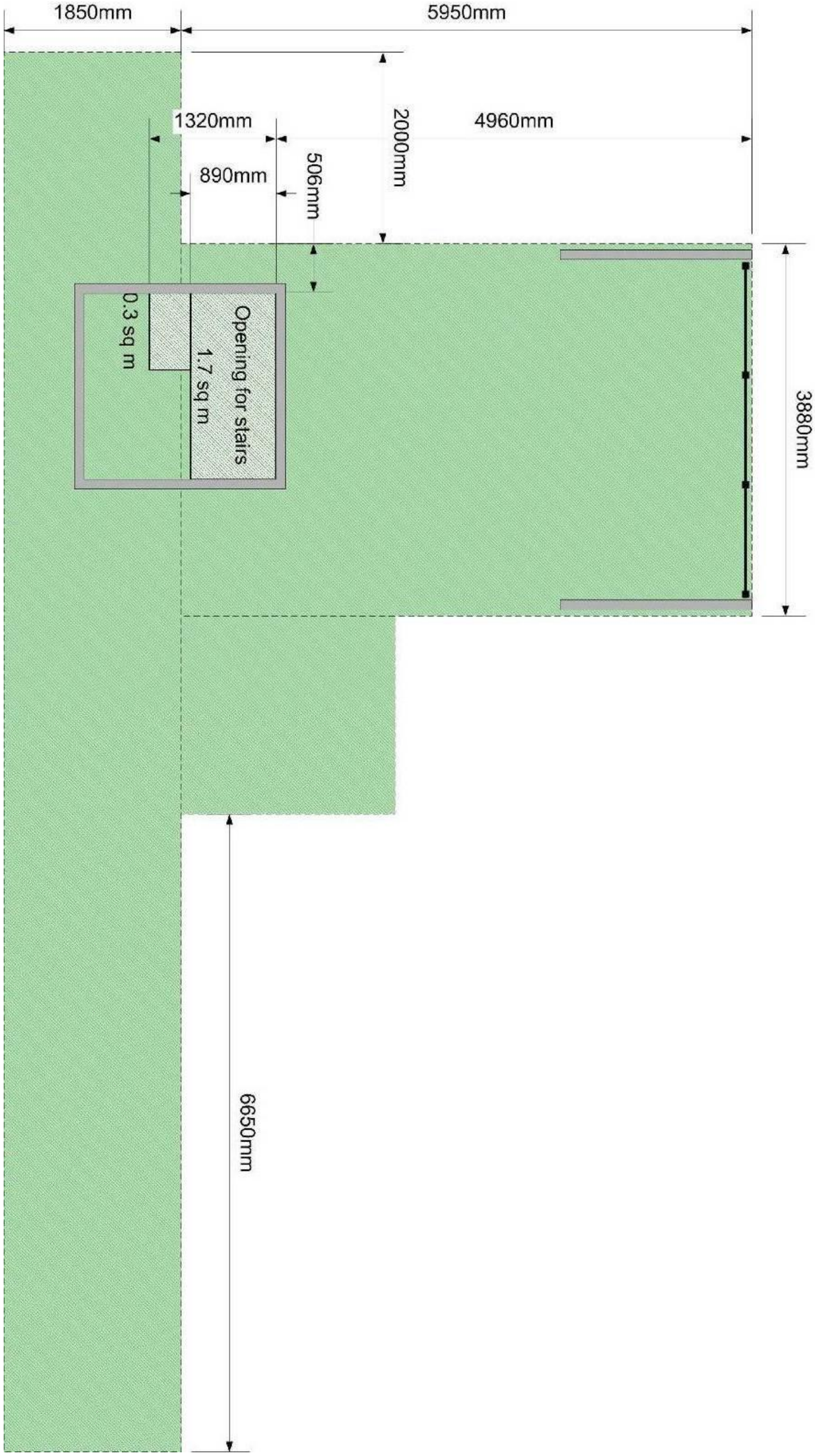


Figure 62 – Upper floor plan of the reconstruction rig[140]

The rig was built using a basic structure of blockwork walls and a pre-cast concrete roof/1st floor. These core construction materials were chosen to be analogous with those of Lakanal House (cast-in-situ concrete) in terms of thermal properties whilst permitting reasonably rapid safe construction. Fixtures, fittings and contents for the rig were either taken from Lakanal House, or chosen by LFB to be as representative (both in terms of fire load and appearance) as possible of the contents of Lakanal House and Flat 79.

The reconstruction fire was designed to develop on as similar a fuel package and constrained by as similar a geometry as was the case in Flat 79 of Lakanal House as possible. The inclusion of a closed headspace above the staircase also allowed the fire to interact with the staircase in a similar fashion to the case in Lakanal House. The condition of the materials (likely deterioration since original installation in Lakanal House) meant that more robust fixings had to be used in the reconstruction rig than was apparent for these boxes in Lakanal House. However, as discussed later, this meant that if there were to be any difference between the reconstruction and the real incident in Lakanal House, the difference would mean that the scenario that actually occurred was probably more severe than that presented by the reconstruction fire.

The inclusion of flat doors in the reconstruction rig served two purposes. The inclusion of a front door and escape door (both taken from Lakanal House) allowed assessment of both of their performance against the reconstruction fire. The reconstruction fire was designed to develop using as similar a fuel package and constrained by as similar a geometry as possible to the case in Flat 79 of Lakanal House. The doors to bedroom 2 and the bathroom were chosen to be chipboard and hollow core (respectively) so that the performance of these kinds of doors was assessed against the fire environment to which they and the front door (a timber block door) were exposed in the flat lobby in the reconstruction fire.

The panel above the flat front door (taken from Lakanal House) was included and allowed assessment of its performance as the fire spread and developed through the reconstruction rig.

Window sets (taken from Lakanal House) were included in the rig to allow assessment of their performance against two scenarios. Firstly, the windows on the ground floor were assessed against the direct flaming generated by wood cribs (the ignition source, discussed later), with the potential for fire spread to items within the bedroom of the reconstruction rig. Secondly, the window performance were examined on an upper floor against flaming from a fully involved fire in a room below, with the geometry being similar to that between Flat 65 and Flat 79 (i.e. fire room set back from the edge of the floor slab, as was the case with the kitchen and balcony of Flat 65).

There will always be some limitation to the degree to which such an incident is reproduced and it is highly likely that some assumptions will have to be made as a result of information being unavailable or destroyed by the fire event. In this case, it was not possible to reproduce the ambient conditions for the reconstruction. It was noted that the temperature on the date of the reconstruction fire was cooler (~10°C – 15°C) than around Lakanal House (~20°C – 25°C). However, given the severity of the fire, these differences in ambient conditions (also pressure, humidity, etc.) are not considered to have been significant.

It was also not possible to fully recreate the wind conditions and to control the exact direction and velocity of this flow. As well as allowing direct monitoring of the reconstruction fire throughout its development, the main open door of the BRE Burn Hall (was left approximately 1m open during the reconstruction) allowed a net flow of air in towards the front windows of the rig. It was assumed that differences in the fire spread and development would not impact significantly upon the relative performance of the items being subjected to the reconstruction fire. The fire could develop more or less quickly than occurred in Lakanal House, however the level of fire severity at which items would fail would remain the same.

It was only possible to recreate part of Flat 79 of Lakanal House in the Burn Hall. A less severe fire was considered to be preferable in terms of the reconstruction test safety and data interpretation. The dimensions of the reconstruction rig were made as close as possible to those of Lakanal House. However, as Flat 79 and the 11th floor corridor were both significantly damaged by fire (including spalling of concrete), it was not possible to accurately determine the pre-fire dimensions of this specific area for the reconstruction (see Figure 63 and Figure 64). It was assumed that like-for-like measurements taken elsewhere in Lakanal House were consistent with the dimensions of this area and that any differences would not significantly impact upon the fire reconstruction.

Figure 63 – Bedroom 1 of Flat 79[140]

Figure 64 – Ceiling of Flat 79, lower (11th) floor. Note exposure of steel reinforcing bars due to extensive spalling of concrete[140]

The window façade sets used in the reconstruction were chosen to be in as good condition as practicably possibly. However glazing is known to be particularly unpredictable in fire due to its susceptibility to only very minor variations in workmanship and fit.

The door frames and doors for the reconstruction were selected from other flats in Lakanal House, apart from the door to bedroom 1 which was understood to have been replaced by the occupants so was not standard to Lakanal House. During the site investigation there was no physical evidence to confirm the actual construction of the door type. The front door of Flat 79 was assumed to be of timber block construction as this was considered to be the best fire performing of the types of door identified. Two other types of doors were fitted and instrumented as the doors to bedroom 2 and the bathroom (see Figure 49 and Figure 61), so that relative performance could be examined. It was assumed that any difference in the performance of these doors would not have any significant impact on the severity of the reconstruction fire.

A suspended ceiling was installed into the corridor of the rig at a height consistent to that of the suspended ceiling in the corridors of Lakanal House, Figure 65. The suspended ceiling in the communal corridor of Lakanal House, reconstructed as its basic structure (timber frame and panels), was provided with very limited additional fuel (in the form of services within the ceiling void). The experimental reason for this was to minimise any obstruction of camera views in the suspended ceiling. However, there was also a safety requirement to minimise the risk of a significant fire occurring here that could produce flaming directly into the BRE Burn Hall extraction and calorimetry system. It was assumed that the reduced quantity of fuel here would not significantly impact upon the fire growth in the room, although it was expected to limit fire development in the suspended ceiling. The fuel load in the corridor was not intended to replicate that of the corridor in Lakanal House. The corridor was intended to provide a conduit into which the fire and fire gases produced in the room fire could travel so that the performance of the materials that were included could be observed and measured. In addition, full fire involvement of the corridor would have been potentially hazardous to personnel operating the test and to the BRE Burn Hall itself, forcing early termination of the reconstruction fire.

Figure 65 – Supporting structure of suspended ceiling in the communal corridor of the third floor of Lakanal House. Photograph courtesy of London Fire Brigade (see Appendix C)[140]

The flats were known all to have had floating timber floorboard floors over the concrete slabs and a non-floating floor (comprising timber floorboards) was installed into the ground floor of the flat in the reconstruction rig (i.e. the boards were loose laid directly onto the concrete floor of the BRE Burn Hall). The floor in the corridor was made up of plasterboard laid to protect the BRE Burn Hall floor, onto which tiles retrieved from the communal corridors of Lakanal house were laid. It was assumed that this difference would not significantly impact upon the development of the reconstruction fire.

Additional windows were installed on the first floor of the reconstruction rig above the reconstruction fire in order to examine their performance against such a fire; a fully developed fire emitting from a floor below.

The staircase used was taken from Flat 27 of Lakanal House (Figure 66) and modified in accordance with information understood to have been collected by LFB from witness statements and interviews. The staircase was reassembled and fitted into the rig in as similar a fashion as possible to the original, Figure 67. A suitably shaped and sized opening was built into the floor slab of the test rig so that the stairs would fit into it as they had done in Lakanal House.

Figure 66 – Staircase in Flat 27 of Lakanal House, prior to removal[140]

Figure 67 – The staircase and modified partition wall fitted into the test rig[140]

A closed headspace was constructed above the timber staircase of the flat. The headspace was installed for two reasons. Firstly, it would allow flaming to develop over the staircase with a level of restriction that was as similar as possible to that provided by the upper floor ceiling of Flat 79. Secondly, it would act as a smoke and flame reservoir from which measurements could be taken of gas concentrations and radiant heat flux at low level on the upper floor.

The undersides of the stairs were protected with boxes constructed of ceramic fibreboard where they penetrated into the communal corridor. It is understood that in Lakanal House these were intended to provide some level of fire separation between the flats and the communal corridor. The ceramic fibre box in the rig was made up of panels from a number of boxes in Lakanal

House because various components of the boxes had been damaged during disassembly as a result of their friability. The box in the reconstruction rig had to be fixed using fresh nails. The original nails had been successfully removed from these boxes during disassembly, but they were too short and fine to hold the panels in place when reassembled in the rig. It is likely that this is due to the board having dried out and perished since its original installation, lessening the purchase of the nails. The ceramic fibre box was installed to be as typical as possible in its form of construction as of the boxes in Lakanal House. The ceramic board built into the reconstruction rig can be seen in Figure 68. How this arrangement then sits in relation to the corridor, the corridor suspended ceiling and the flat can be seen in Figure 69.

Figure 68 – Mineral fibre box assembly beneath the stairs in the reconstruction rig[140]

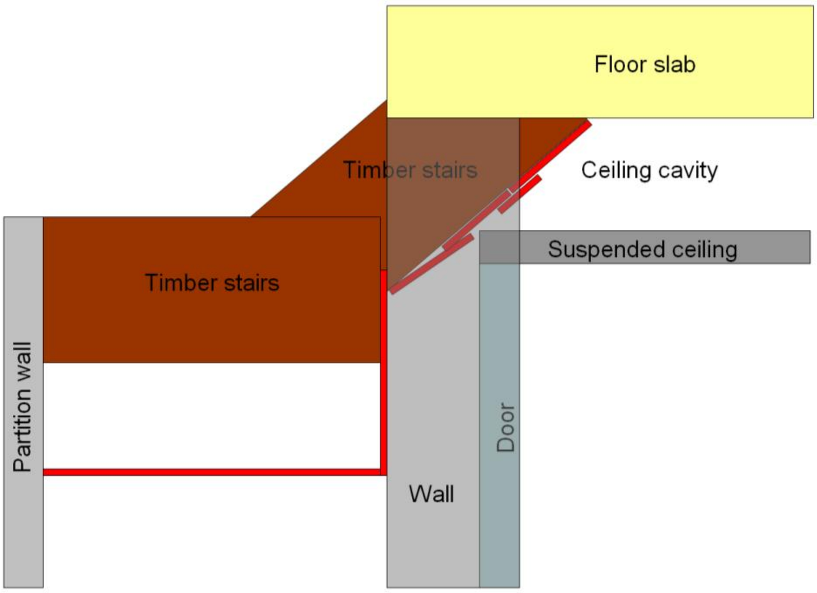


Figure 69 – Elevation section diagram of pieces of mineral fibreboard making up box beneath stairs. Wall position overlaid as transparent block[140]

It was not possible to fully recreate the ignition source for Flat 79 (believed to be flaming coming from Flat 65). A wood crib was designed and used to produce flaming similar to the flame tips coming from a fully involved fire from a flat below, however this could not fully replicate the conditions during the incident. It was also not possible to include exactly the same contents as were present in Flat 79. London Fire Brigade collected information on these contents so that they could be replicated as closely as possible for the reconstruction. It was assumed that any difference in these contents did not impact significantly on the reconstruction fire.

Fixtures and fittings for the rig were taken from Lakanal House, but it was not possible to use materials that had actually been involved in the fire due to their damage or entire fire consumption. Selection of fixtures and fittings were in as good condition as reasonably practicable and therefore any differences in performance would tend towards creating less severe conditions from those in the actual incident. It is understood that a number of aerosol cans containing pressurised flammable gas propellant were present in Flat 79. It was not possible to include these in the reconstruction fire due to the experimental safety risk associated that would be associated with rupture and explosion of these cans during the reconstruction fire. Firelighters were used to provide an equivalent, albeit non-explosive, source of fuel to represent these aerosol cans.

The contents for the room as well as some of the details for the fixtures and fittings were all specified by LFB, with the exception of aerosol cans; it was not possible to include any aerosol cans in the fire due to the hazard they would present to test personnel if they exploded during the reconstruction fire. The contents of the rig were as follows:

- Barber’s chair
- Trestle tables x2
- Decorating table
- Sewing machines x2
- Mannequin
- Boxes full of hairdressing supplies
- Bin bags full of hairdressing supplies
- Chest of drawers

- Hanging wardrobe
- Bookcase full of books
- Chair
- Tabletop
- Bike
- Sofa
- Office chair
- Fire-lighters with a mass approximately equal to that of the mass of propellant in aerosols understood to have been in Flat 79 were included with the hairdressing supplies

3.1.3.1. Instrumentation

The layout of the instrumentation within the reconstruction rig can be seen in Figure 72 and Figure 73. Columns of thermocouples (thermocouple trees) were installed at key locations throughout the rig. Thermocouple columns were installed in the following locations:

- One was installed at either end of bedroom 1 (one metre from the window end and one metre from the partition wall against the staircase, both along the centre line of the room).
- One was installed up through the staircase, including the cupboard underneath the stairs and the headspace above, located centrally through the turn in the stairs.
- Two were in the lobby of the flat, located on the centre equidistant from the wall of the communal corridor and the wall of bedroom 2, each tree half a metre from the end of this line.
- Three were installed in the communal corridor; one located centrally outside each of the doors and a third one, one metre from the extract grille at the end of the corridor.

All doors were instrumented with thermocouples fixed to both major surfaces at quarter positions (i.e. one quarter of the full width and one quarter of the full height in from the edges). Thermocouple positions on the doors are all labelled from the perspective of bedroom 1 (i.e. the inside face is the face nearest bedroom 1, and left and right are marked as seen from bedroom 1).

The panels above the doors were also instrumented using thermocouples. The panels above the doors to bedroom 1, bedroom 2 and the bathroom were all instrumented with two thermocouples; one in the centre of each side of the panel. The panel above the front door was instrumented with four thermocouples; two on either side each located halfway up the panel and one quarter of the total panel width in from either end.

The windows of the reconstruction rig were instrumented with thermocouples. The lower floor set of windows simply had a series of external surface thermocouples up the middle of each of the three sections of the window set. The upper floor set of windows had internal and external thermocouples at the centre of each of the three panels and each of the three main (larger) glazed areas.

Heat flux meters were installed in three locations on the reconstruction rig, Figure 72 and Figure 73. A heat flux meter was installed adjacent to the upper window set so that radiant heat flux from any flaming below could be quantified. Another heat flux meter was installed on the floor of the headspace above the timber staircase, oriented upwards so that it would measure downward heat flux from a hot layer in the headspace. The third heat flux meter was installed on the floor of the corridor outside the fire escape door under the stairs, also oriented upwards, so that any downward heat radiation could be measured and quantified.

Continuous gas sampling for CO, CO_2 and O_2 as well as discrete samples of HCN, HCl and HBr was undertaken at low level in the headspace above the timber staircase, see Figure 70 and Figure 71. This was to provide some indication of the relative concentrations of toxic gases to which the occupant of Flat 79 was exposed during the incident (concentrations measured here could not be related directly to possible conditions during the incident because the headspace was a much smaller, and more sealed volume than the upper floor of Flat 79).

Figure 70 – Gas sampling points at top of staircase in headspace of reconstruction rig[142]

Figure 71 – Gas analysers for continuous gas analysis and bubblers for discrete samples[142]

The duct of the extraction grille was fitted with gas sampling, temperature and flow measurement equipment to create a second calorimeter for the test. This corridor extraction and calorimetry system was set to extract at a volumetric rate that would generate a 0.1m/s linear velocity at the downwind end of the corridor, replicating the corridor conditions identified by the preliminary computer modelling.

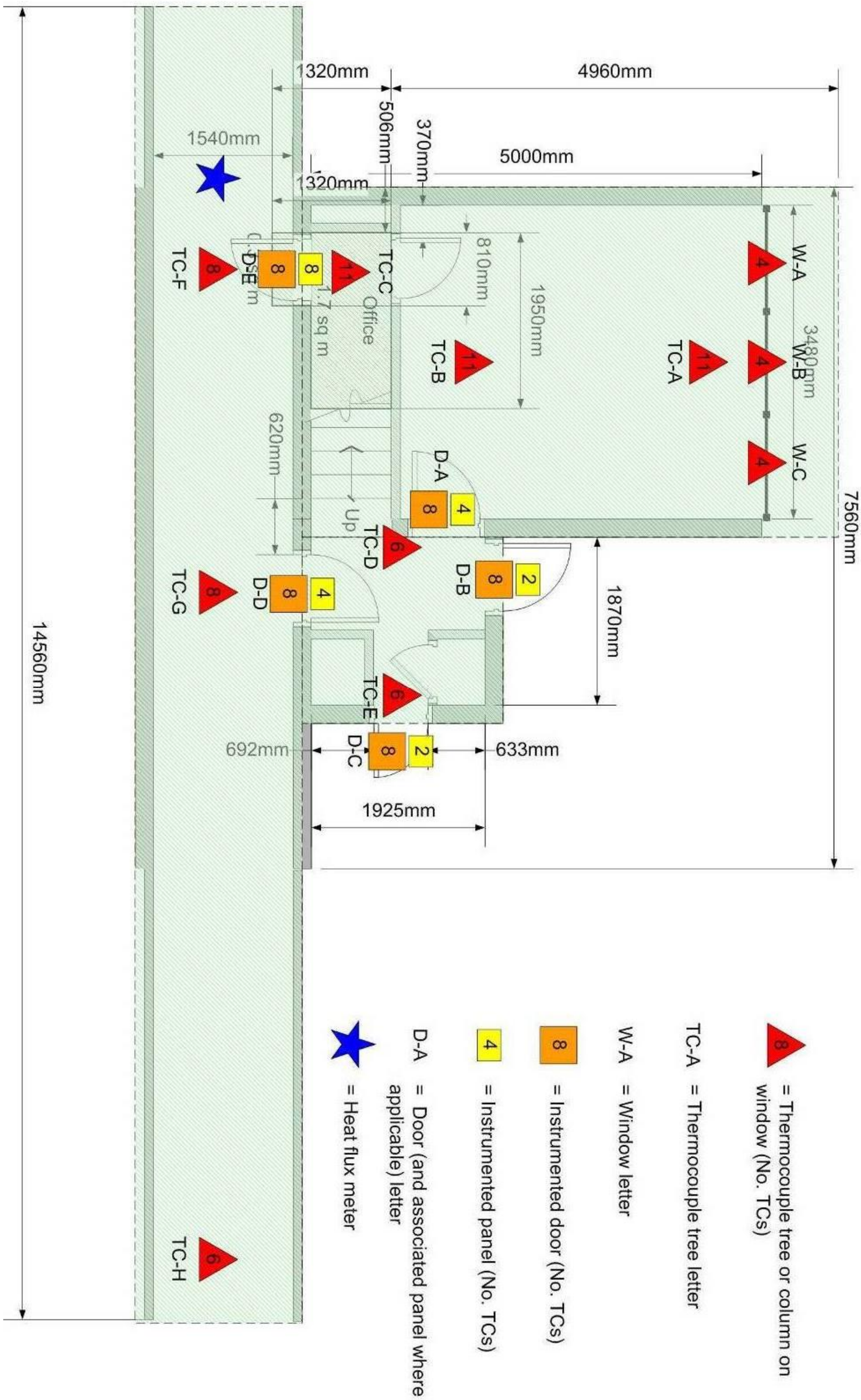


Figure 72 – Ground floor plan of the reconstruction rig instrumentation[140]

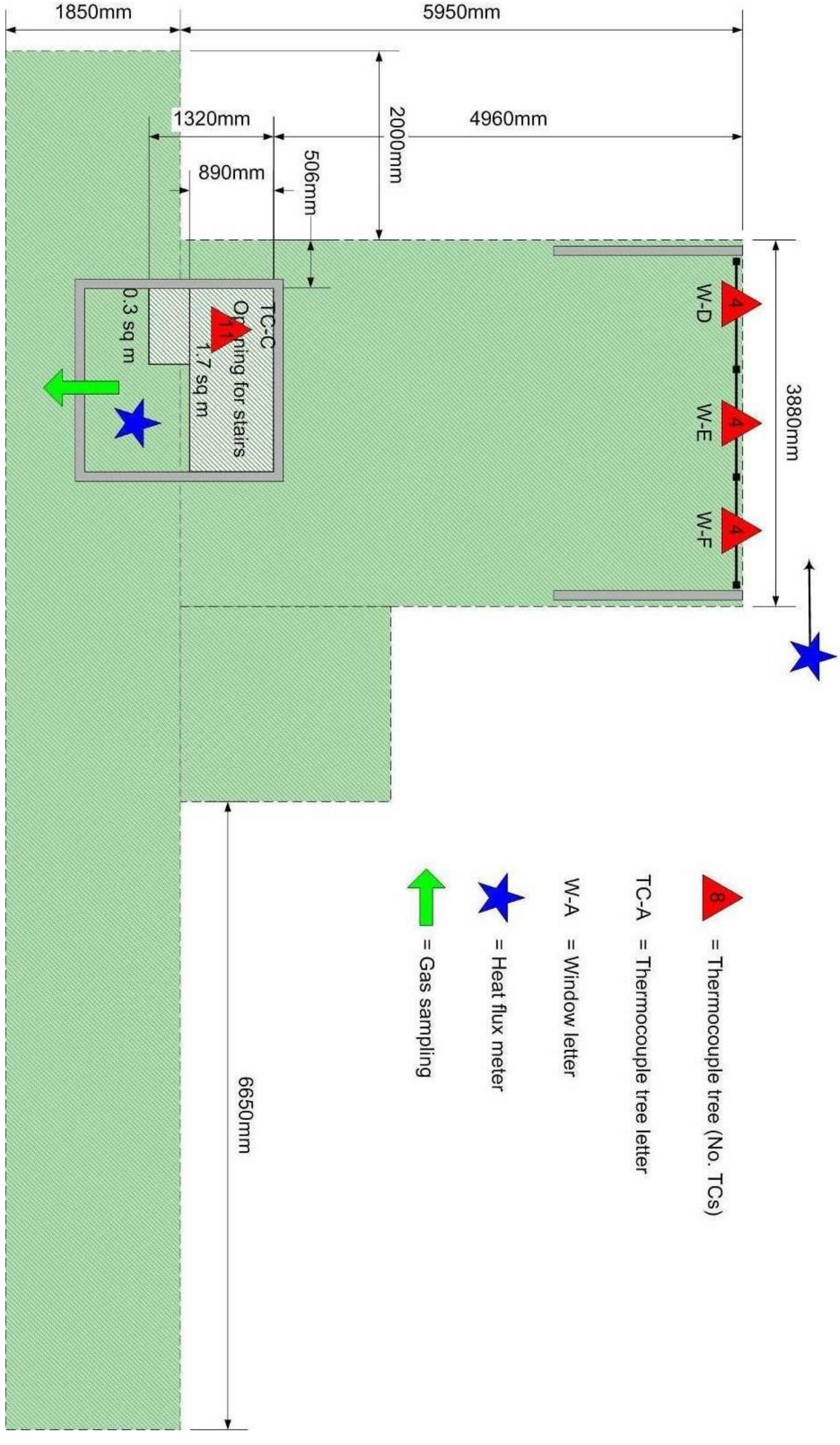


Figure 73 – Upper floor plan of the reconstruction rig instrumentation [140]

3.1.4. **Reconstruction Results**

The ignition source for the reconstruction fire was a set of three wood cribs, designed to provide a fire source as similar as possible to the flaming that was understood to have impinged upon the window of bedroom 1 of Flat 79 from the fire in Flat 65 below.

This crib design was calculated to produce a flame height of approximately 1.2m and a heat flux of just over 30kW/m^2 at 0.3m from the centre of the longest side of the crib. The cribs can be seen in situ in Figure 74.

Figure 74 – Wood cribs in place in front of windows of reconstruction rig [140]

The test was started by igniting the wood cribs situated in front of the lower floor windows of the reconstruction rig. A series of fibre sticks soaked in white spirit were arranged in the spaces in the lowest layer of the cribs and ignition was initiated using a blowtorch.

The fire was allowed to develop, grow and spread without interference until the decision was taken to terminate the fire approximately 90 minutes into the test (at this time only minimal fire fighting and damping down was required). Observations are presented in Table 17.

Time from ignition (minutes:seconds)	Event	Seen on camera number
0:00	Ignition of fuel package outside window	9
1:14	Panel A well alight	9
1:27	All three lower floor panels well alight	9
1:42	Smoke entering bedroom	8
2:37	Fire impinging on window	11
2:00 – 3:00 (approx.)	Light smoke throughout high level of bedroom	8
3:00 – 4:00 (approx.)	Light smoke in front of camera	8
4:05	Outer glass pane of window C fails	9
4:15	Flaming visible behind upper corner of panel A	9

Time from ignition (minutes:seconds)	Event	Seen on camera number
4:21	Fire involving curtains near window A	10
4:22	Fire involving curtains near window A	9
4:22	Fire involving curtains near window A	11
4:47	Flames at bottom of curtain near window C	8
5:10	Fire involving curtains near window C	8
5:10	Curtain near window C alight	9
5:26	Window C fails	9
5.30	Window A fails	9
5:40 (approx.)	Plaster falling from ceiling	10
6:17	Room blacked out with smoke	11
6:39	Panels fail/fall away	9
7:01	Flames on front of camera 8	8
7:57	Flaming at front of room becomes visible as smoke lifts	10
8:05	Front of room alight	11
8:07	First flame to 1st floor level	9
8:37	Fire on right of view of camera 6	6
8:57	Items in front of camera 8 alight	8
9:07	Plastic boxes fall over into fire at trestle tables near window	8
9:18	Window B fails	9
9:45	Flame seen through window F (upper level)	13
10:30	Flame seen through window D (upper level)	13
10:37	Camera 8 fails	8
11:37	Fire involving the wardrobe	10
12:02	Front of room alight	11
12:29	Flames in front of camera 10	10
12:37	Decorating table alight	6
13:07	Fire at the sofa adjacent to the stairs	11
13:17	Window frame collapses	9
13:24	Window frame falls away	9
13:24 – 14:08	Regular flaming to 1st floor level	9
13:27	Camera 6 fails	6
13:49	Camera 10 fails	10
15:00 (approx.)	Seal around window panel F starts to distort	13
17:27	Sofa adjacent to stairs alight	5
17:37	Fire in the front of room decaying	9
20:00 (approx.)	Camera 13 view obstructed by smoke	13
20:37	Staircase alight	5
21:27	Fire at stairs increasing	9
21:27	Fire behind the flat entrance door	3
22:37	Stairs structure alight	5
23:37	Glow under the fire door	1
24:17	Fire breaks through entrance door into corridor	3
25:07	Flames issuing the letterbox and top of entrance door	3
25:23	Bottom of entrance door alight	1
25:45	Entrance door alight	1
26:37	Entrance door alight	4
27:37	Flame observed at fire door	1
27:59	Fire door alight in the corridor	1
34:00 – 36:00 (approx.)	Fire in bedroom 1 dies down	9
38:00 (approx.)	Increase in flaming at rear of bedroom 1	9
38:00 (approx.)	Flaming becomes visible in vicinity of panel above front door	12
39:29	Intermittent flaming extending from rear to front edge	9
40:44 – 45:03	Regular flaming extending from rear to front edge	9
42:37	Top and bottom areas of entrance door alight	3

Time from ignition (minutes:seconds)	Event	Seen on camera number
50:00 (approx.)	Flaming becomes visible in vicinity of ceramic fibreboard box	2
54:32	Entrance door and frame fall into corridor	4
54:32	Entrance door and frame fall into corridor	1
54:32	Entrance door and frame fall into corridor	3
67:22 – 68:32	Flames spread to fully involve escape door	1
70:01	Escape door collapses into corridor – frame remains in situ	1
85:38	Test terminated	9

Table 17 – Significant observations from video footage of reconstruction

3.1.4.1. Data from the Thermocouple Trees

Temperature data collected from thermocouple trees A and B are presented in Figure 75 and Figure 76. The layout of the instrumentation throughout the reconstruction rig is shown in Figure 72 and Figure 73.

The data from thermocouple tree A show a rapid temperature rise in the vicinity of the bedroom window associated with the fire breaking through from outside and then involving various significant items in that area. The temperatures then decay as the fire moves towards the rear of the bedroom (nearer the stairs) but remain steady as a result of the continued heat release from other burning items until late into the reconstruction burn.

Temperatures at thermocouple tree B confirm the pattern of spread towards the rear of the compartment as the temperatures here peak approximately 5 minutes later than at thermocouple tree A. There are intermittent increases in temperature at individual heights on this tree, likely to be due to the relative proximity of thermocouple tree B to items involved in the fire later on in the test. However, it is not possible to confirm which items are responsible for this, as cameras focussed on this area did not survive at this time.

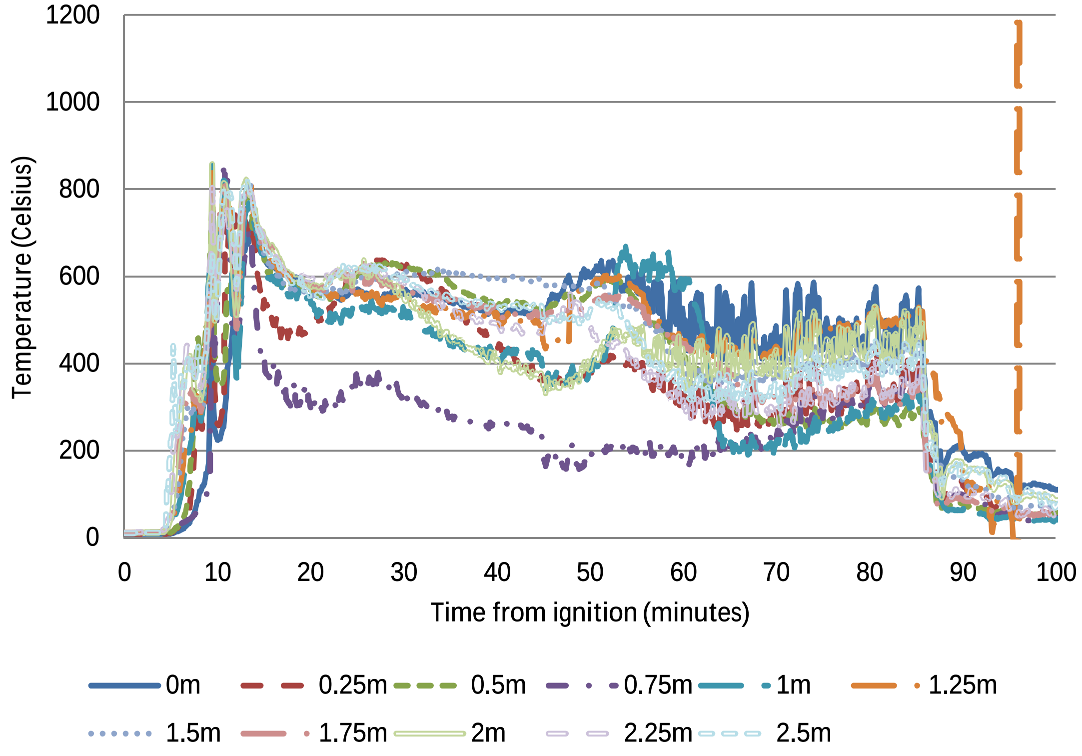


Figure 75 – Temperature data at thermocouple tree A. The sharp peak at 97 minutes is an open/short circuit error, likely the result of damage to thermocouple leads and/or application of water[140]

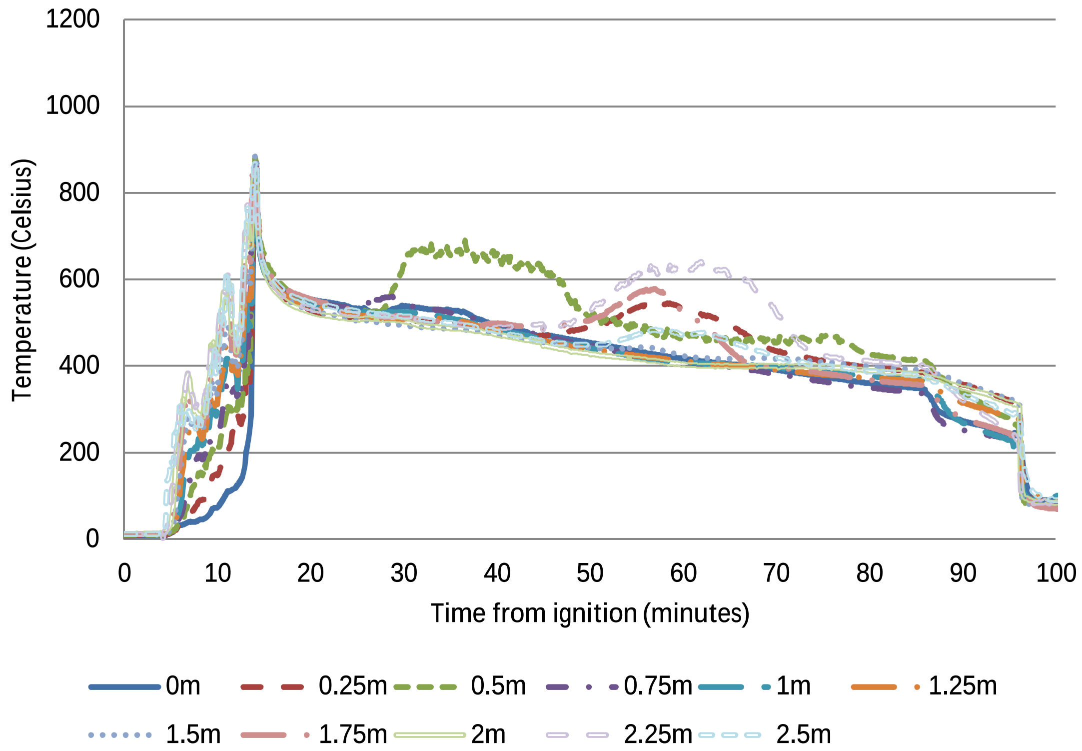


Figure 76 – Temperature data at thermocouple tree B[140]

Thermocouple trees C, D and E all measured an initial temperature increase associated with the fire developing from the window and spreading into the room. However the most significant increase in temperatures in this region of the reconstruction rig appears to be associated with the ignition of the staircase. All three locations experienced a peak temperature of around 900°C in the ten minutes following the ignition of the staircase. This second fire peak (second to the initial smaller peak caused by burning near to the window) is likely to be responsible for the failure of components following shortly afterwards. A further peak in temperatures is measured at thermocouple tree D, which coincides with the failure of door B. There is also an associated increase in the temperatures measured at door A. The temperature data obtained from thermocouple trees C, D and E are given in Figure 77 to Figure 79.

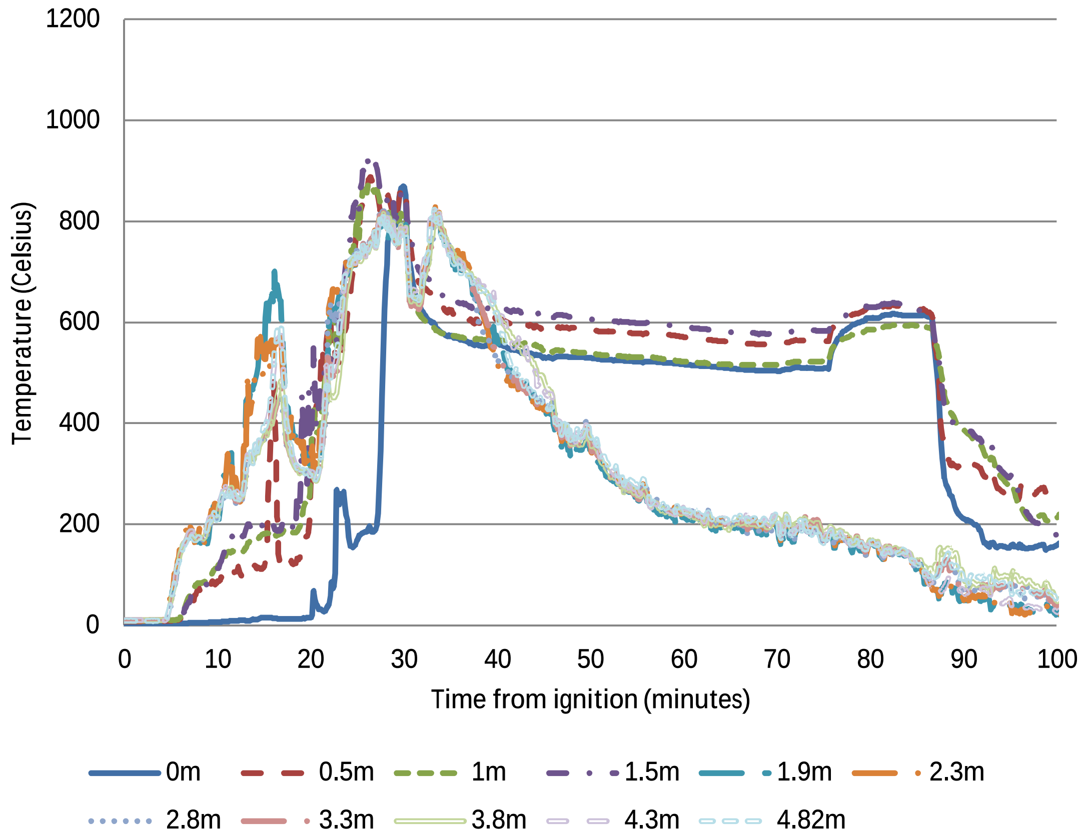


Figure 77 – Temperature data at thermocouple tree C[140]

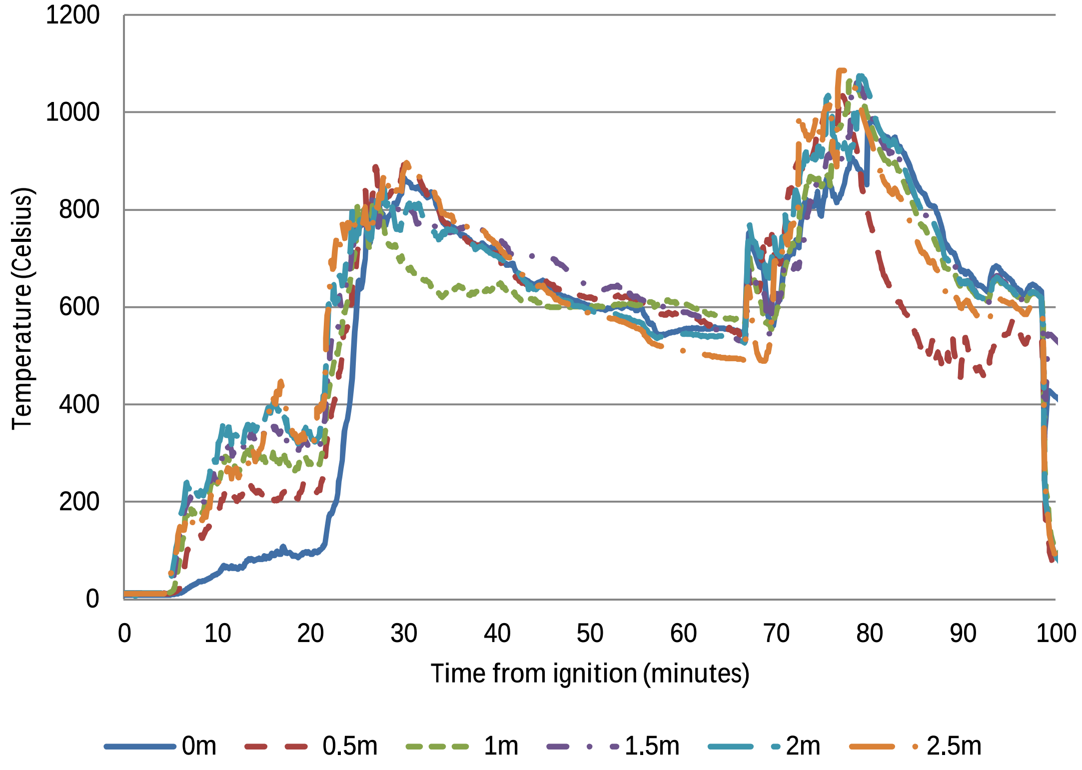


Figure 78 – Temperature data at thermocouple tree D[140]

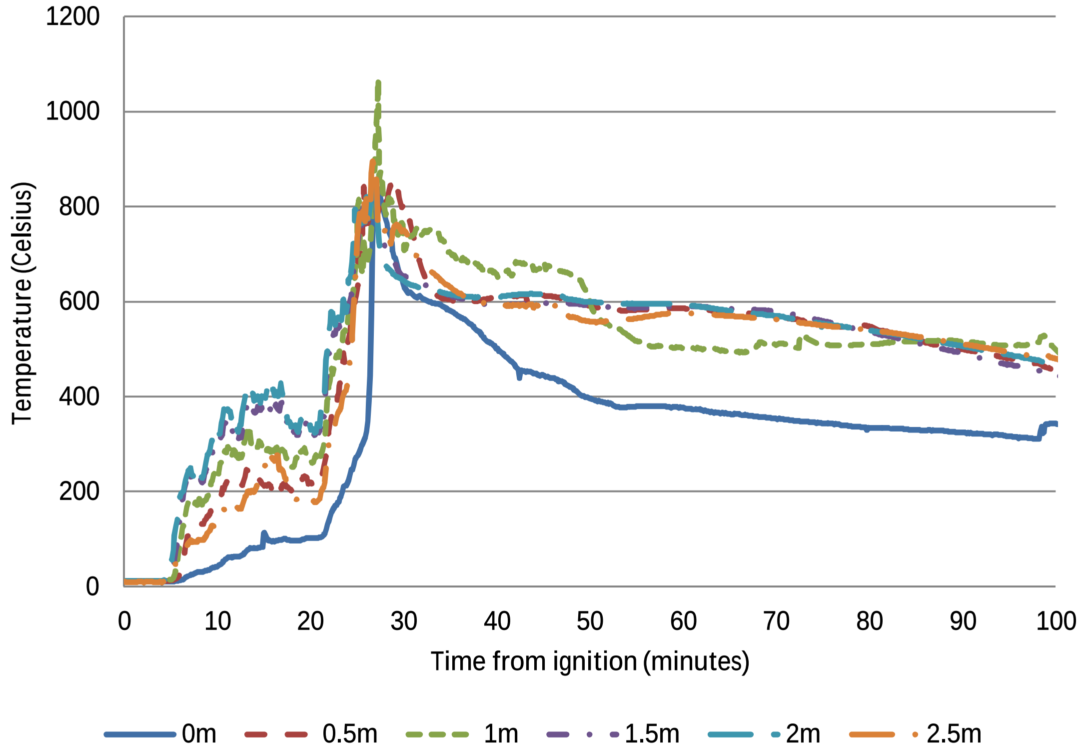


Figure 79 – Temperature data at thermocouple tree E[140]

Thermocouple tree F in the corridor (Figure 80) near the escape door measured temperature increases at high level within the corridor and suspended ceiling void that correspond well with the fire events that occurred on door E and the ceramic box beneath the stairs. In particular, temperatures in the ceiling void approached 700°C around the time when well-developed flaming is seen in the vicinity of the ceramic fibreboard box.

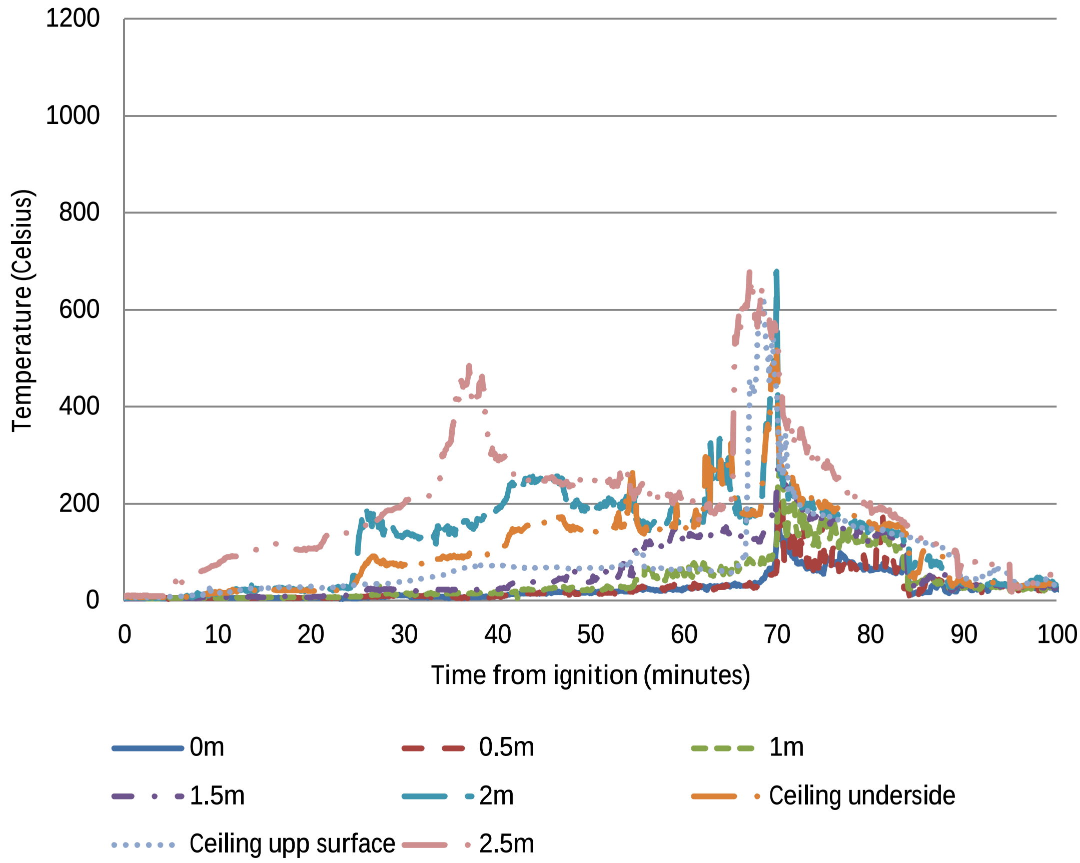


Figure 80 – Temperature data at thermocouple tree F[140]

Thermocouple tree G, outside the front door (Figure 81), shows how fire penetration through the front door and panel affected the temperatures in this area. Temperature increased at high level within the corridor occurred shortly after the door began burning on its outer (corridor) side, going through an initial gradual increase and decay, followed by a sudden increase to 800-900°C when the door and frame collapsed into the corridor. The temperature measurements in the ceiling void follow a similar trend, although the initial temperature rise corresponds to the flaming that is seen in the void around 38 minutes into the reconstruction.

Temperatures measured at thermocouple tree H near the corridor extract (Figure 82) remained relatively low throughout the test, although there are minor peaks associated with the fire involvement and collapse of doors mentioned earlier.

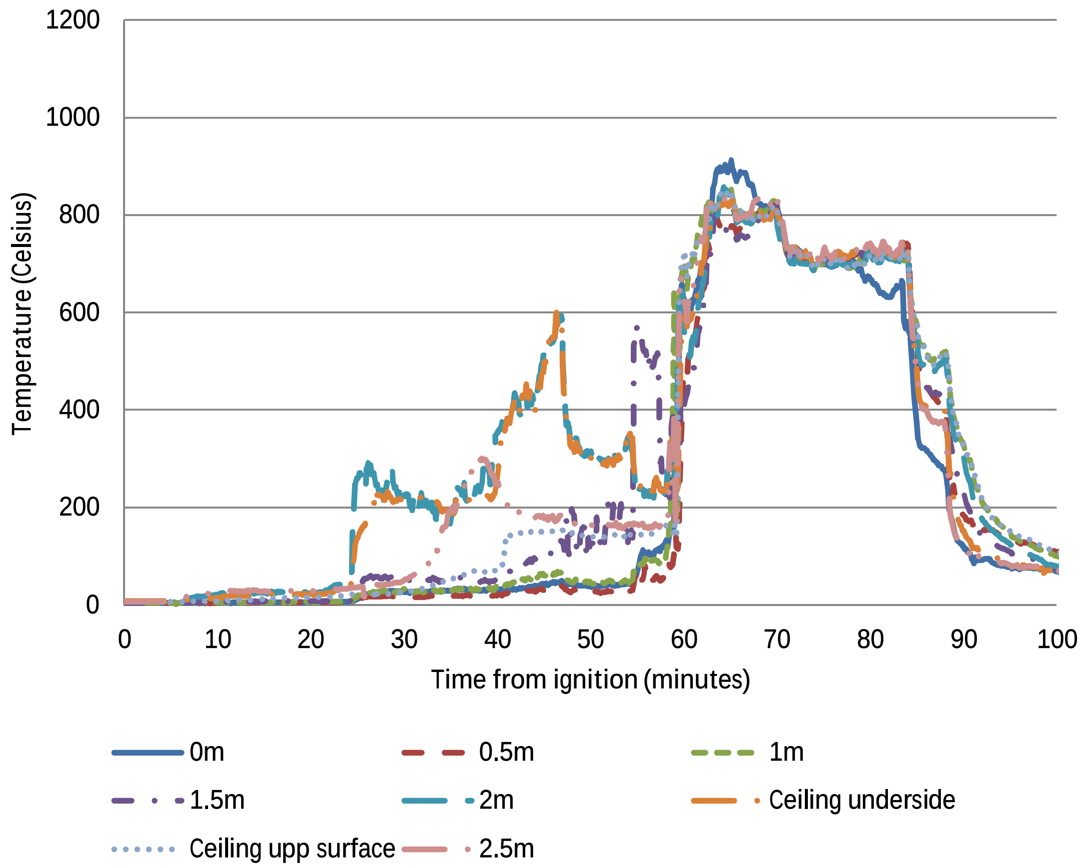


Figure 81 – Temperature data at thermocouple tree G[140]

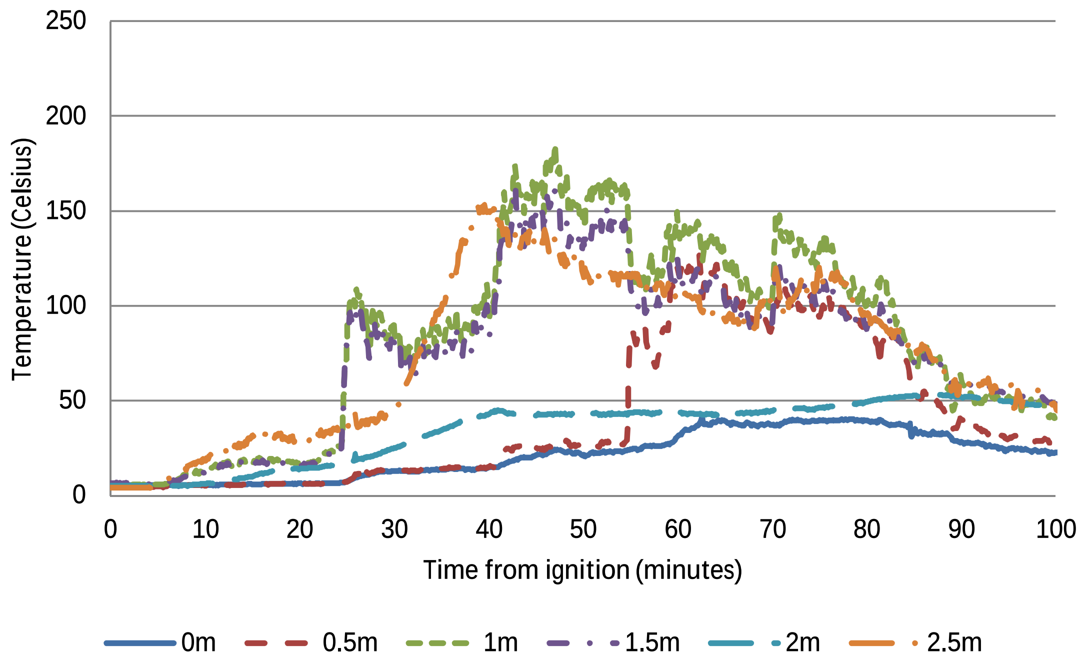


Figure 82 – Temperature data at thermocouple tree H[140]

High temperatures were measured at high level on thermocouple trees F to H and there was direct flame impingement of these thermocouples. However, the suspended ceiling did not become a contributing fuel source during the duration of the reconstruction.

3.1.4.2. Data from the Thermocouples Installed on the Window Sets

The thermocouples installed onto the lower window set: windows A, B and C (Figure 83, data in Figure 84, Figure 85 and Figure 86 respectively) of the reconstruction rig (all external) initially confirm rapid fire involvement of the wooden cribs used as the ignition source and consequential rapid surface temperature rise of the window assemblies. The reason for the noisiness of the data is that these thermocouples are exposed to direct flame impingement, so temperatures fluctuate as flames pass over them.

Figure 83 – Lower floor window set showing labelling of windows [140]

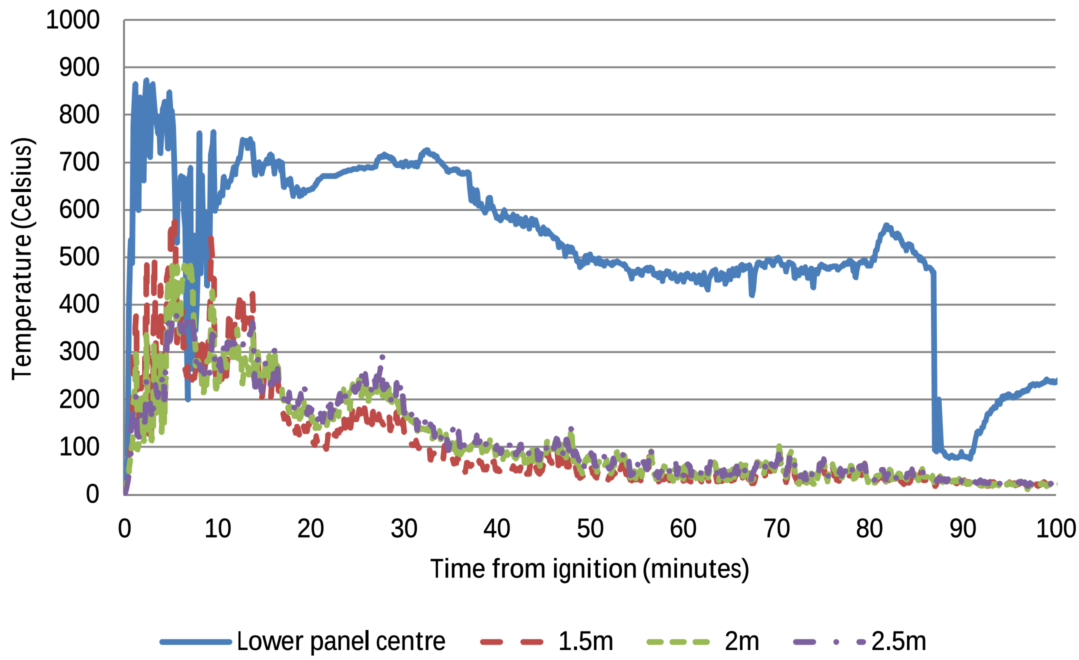


Figure 84 – Temperature data at thermocouple positions on window A[140]

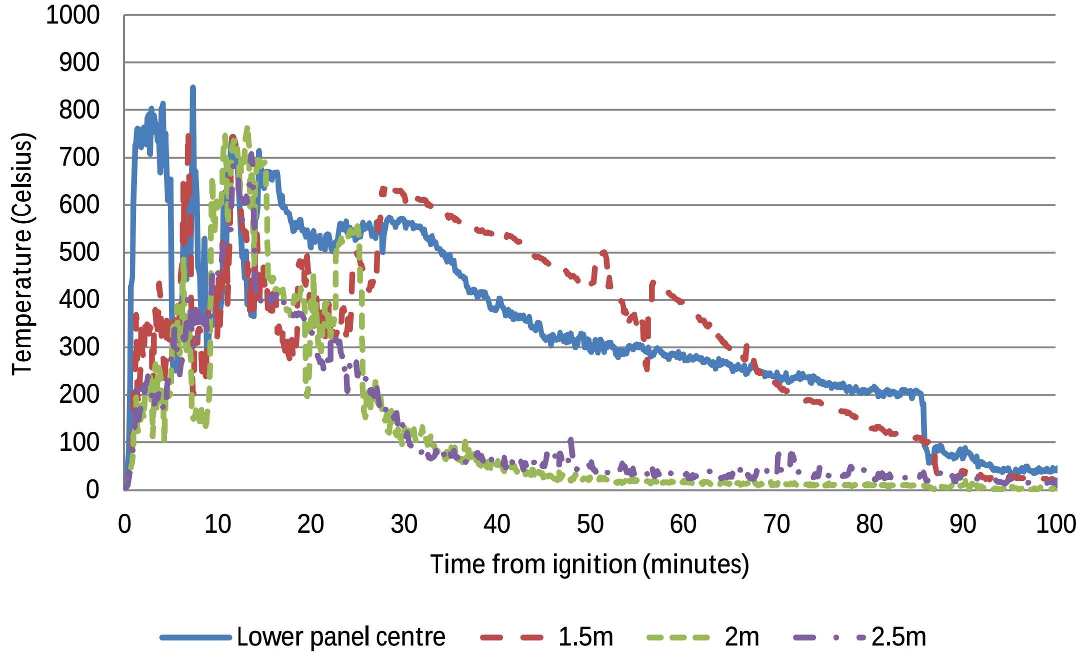


Figure 85 – Temperature data at thermocouple positions on window B[140]

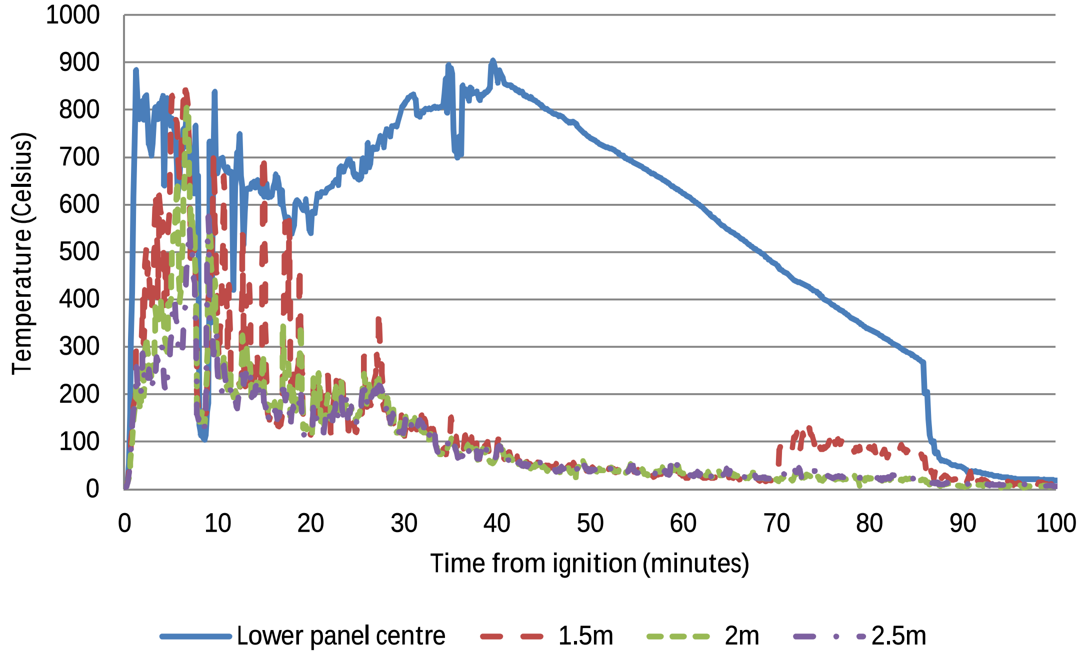


Figure 86 – Temperature data at thermocouple positions on window C[140]

The thermocouples installed on the upper window set (see Figure 87) show high external temperatures associated with periods of intermittent and (marked in orange) regular flaming at the upper level. Of particular interest are the periods of regular flaming around 25 minutes. On both windows D and E (Figure 88 and Figure 89), where external temperatures reach 300°C-400°C, there is a sudden increase in the internal surface temperature of the panel immediately prior to the period of regular flaming ending. On window F (Figure 90), where external temperatures only reach around 170°C-280°C during this period, there is no associated sudden increase in internal surface temperature of the panel.

Figure 87 – Upper floor window set showing labelling of windows [140]

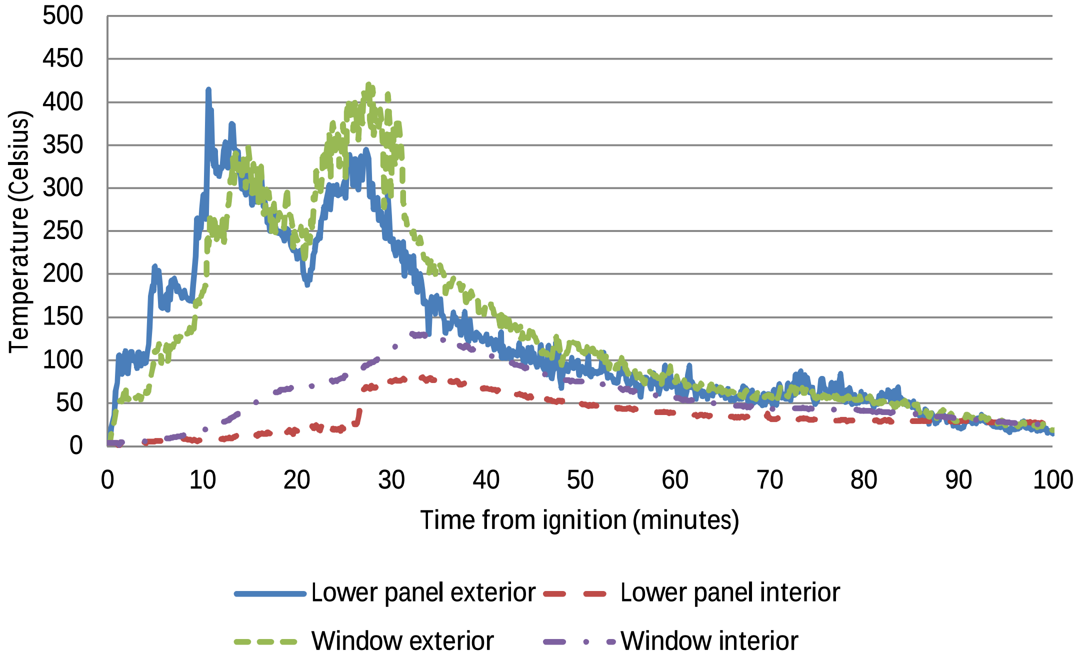


Figure 88 – Temperature data at thermocouple positions on window D [140]

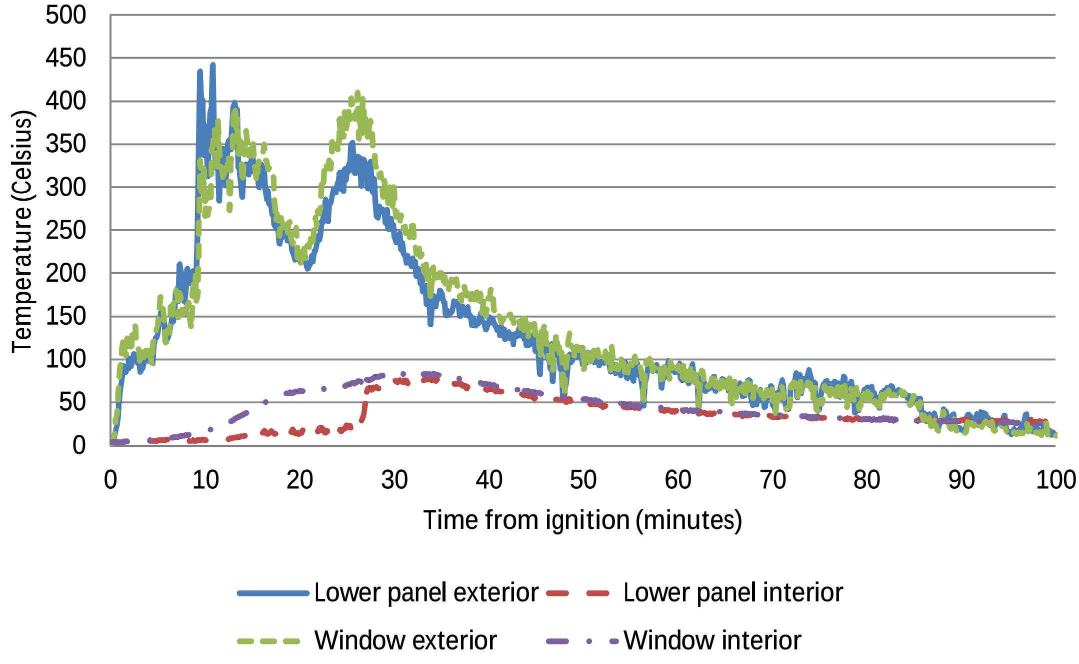


Figure 89 – Temperature data at thermocouple positions on window E [140]

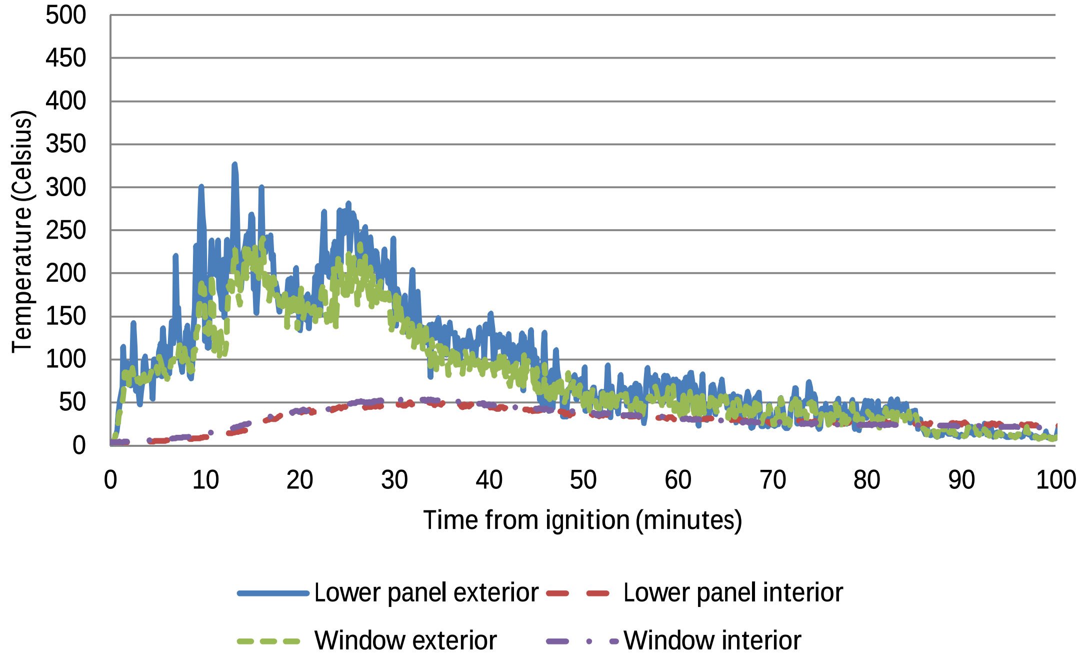


Figure 90 – Temperature data at thermocouple positions on window F [140]

The window panels on the upper level of the reconstruction rig did not sustain ignition or burn through during the fire. However they were significantly scorched and did undergo distortion as well as the pattern of temperature rises detailed above (see Figure 91). This indicates that although ignition did not occur, conditions any worse than those produced during the reconstruction would very likely have led to these panels becoming involved.

Figure 91 – Upper floor window set showing damage to glazing plus scorching and distortion of window panels. Photograph courtesy of MPS (see Appendix B) [140]

3.1.4.3. Data from the Thermocouples Installed on the Doors

The data plots for doors A-E and the ceramic box beneath the stairs are shown in Figure 92 to Figure 98.

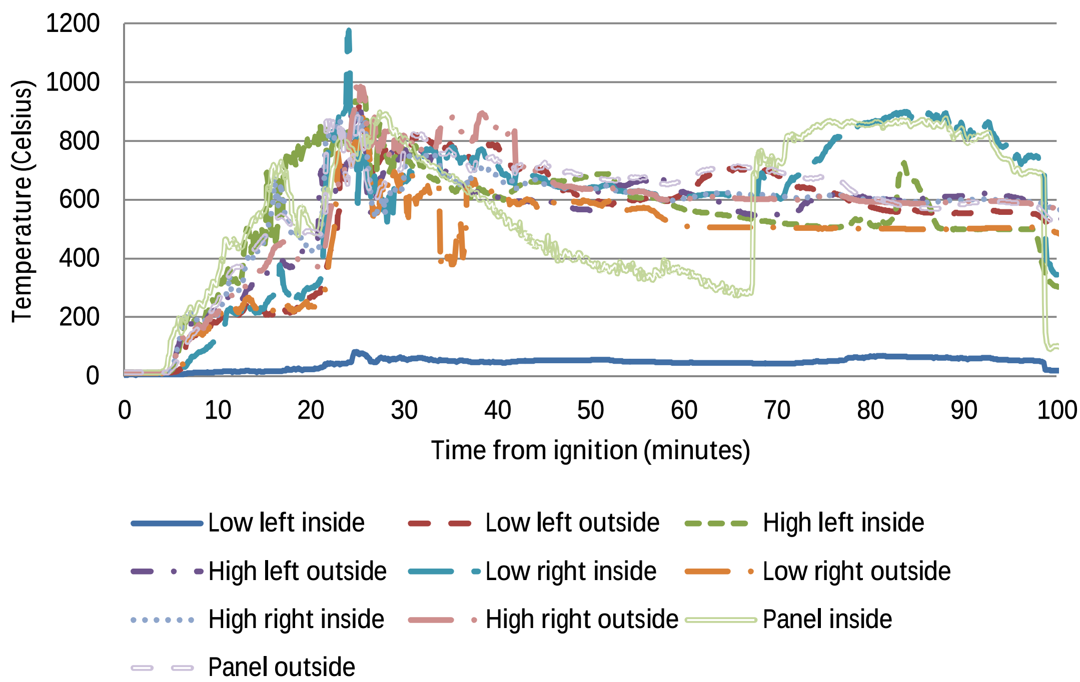


Figure 92 – Temperature data at thermocouple positions on door A [140]

The temperature data obtained from door A are very similar to (but noisier than) the temperature data obtained from thermocouple tree D in Figure 78. This is likely due to the two being near to one another, but the thermocouples on door A were in close proximity to a number of fuel beds (door A itself and the bookcase) meaning that these are exposed to direct flame impingement at various points throughout the test. It is worth adding that at some point, door A was fully consumed by the fire so will have collapsed, leaving the thermocouples to fall to the floor.

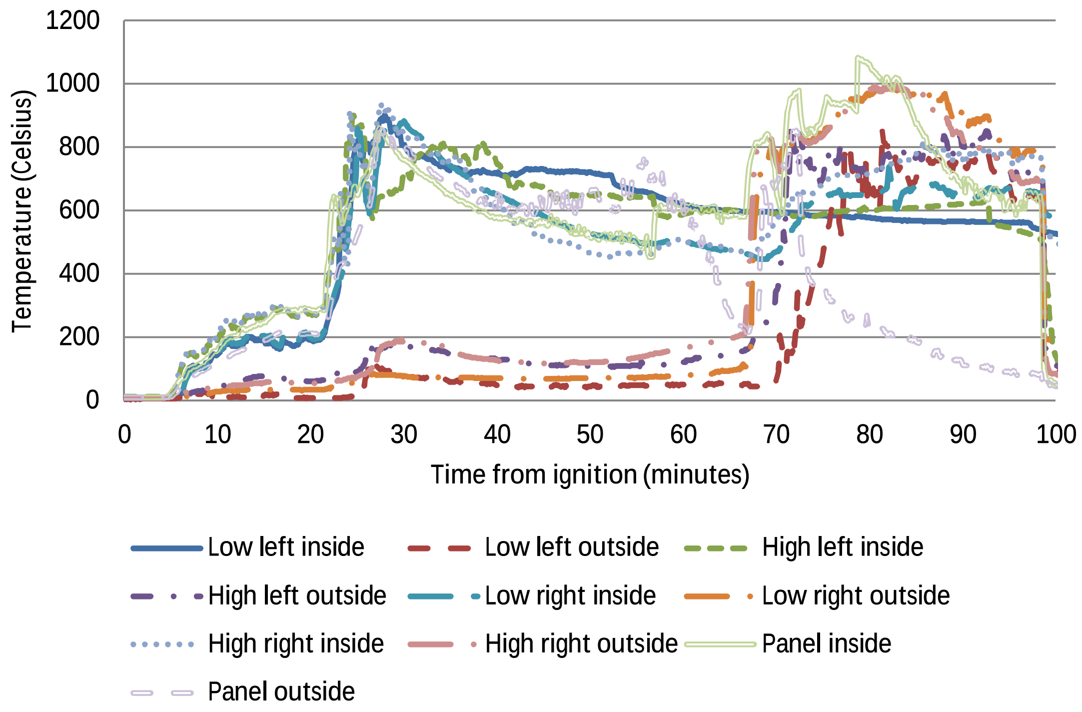


Figure 93 – Temperature data at thermocouple positions on door B[140]

According to the interior surface thermocouples, doors B and C experience a gradual temperature increase to around 300°C during the first 20 minutes of the reconstruction. At this time the stairs become involved and they become exposed to fire temperatures in excess of 800°C around five minutes after this. Door B, the chipboard door, appears to retain its integrity for approximately 45 minutes following the increase in temperature, at which time the external thermocouples measure temperature increases from less than 250°C to more than 750°C. Door C, the hollow core door, fails during the five minutes after becoming exposed to the fire associated with the involvement of the staircase.

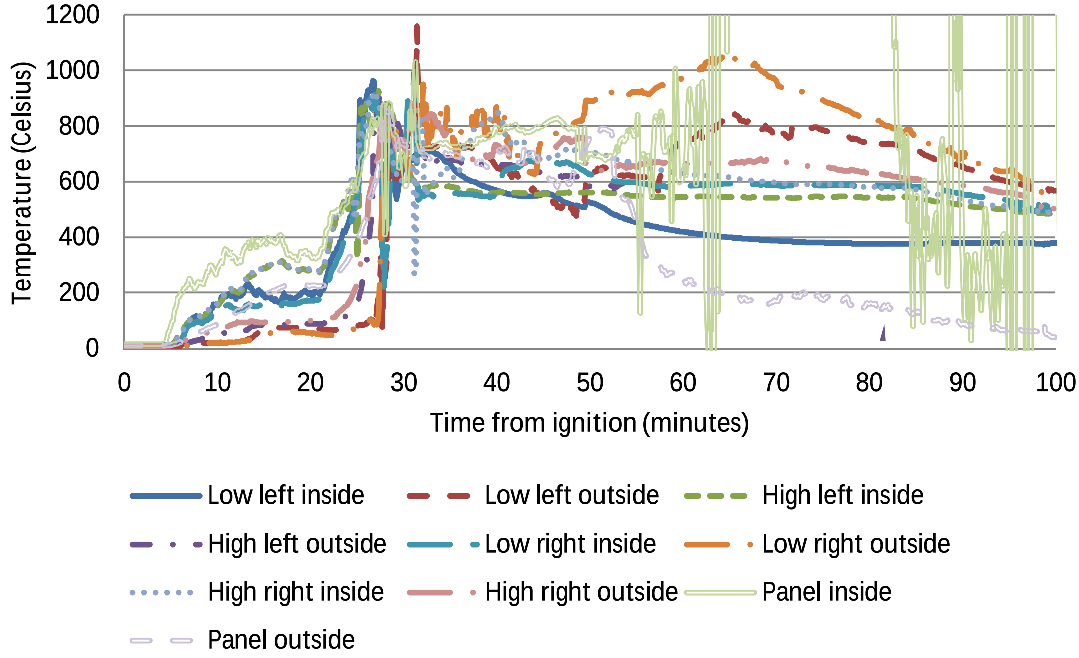


Figure 94 – Temperature data at thermocouple positions on door C[140]

Door D, the timber block front door, was exposed to a very similar temperature regime to doors B and C, although the internal surface of the panel above the door reaches over 550°C during this time, probably due to the surface being combustible (unlike the glazed panels above doors A, B and C) as well as being high up in the hot gas layer caused by the fire. This door became involved on both surfaces within five minutes of the staircase becoming involved. From the video footage it can be seen that this is a result of fire penetrating through both the letter box in the door and the gaps between the door and frame, then spreading across the painted surface of the door. The door burned in situ for approximately 30 minutes, during which time the fire it was producing attacked the suspended ceiling of the corridor, before collapsing with its frame into the corridor itself (a total of approximately 55 minutes since ignition). The damage caused to the corridor suspended ceiling outside this door can be seen in Figure 95.

Figure 95 – Space formerly occupied by door D; the flat front door, following the reconstruction fire. Note severe damage to suspended ceiling panels, but no self-sustaining ignition of panels[140]

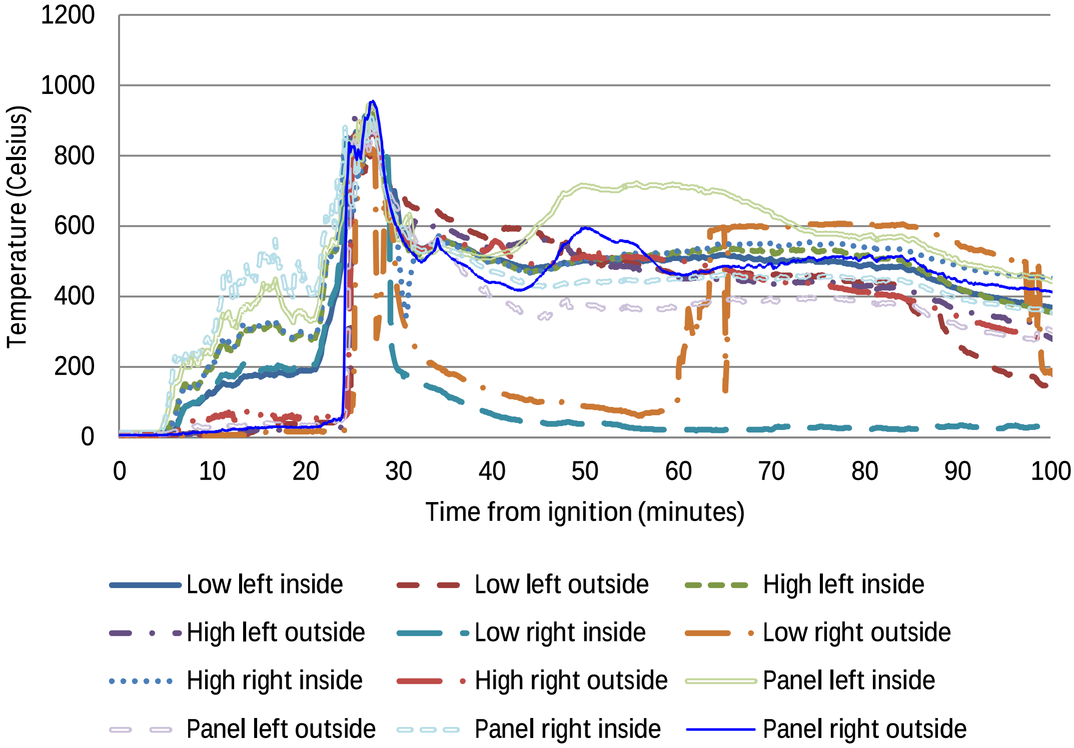


Figure 96 – Temperature data at thermocouple positions on door D[140]

The panel above the front door appeared to fail (indicated by sudden increase in outside surface temperatures) approximately 20 minutes after inside surface temperatures exceed 200°C, and approximately four minutes after the involvement of the staircase.

The temperatures recorded for door E indicate that it was somewhat shielded from the heat of the fire, temperatures only attaining 150°C until the staircase became fully involved. Flaming was seen at the gap between the door and frame 5-10 minutes after the involvement of the stairs, which continues to burn and propagate until it spreads to involve the entire outer (corridor) surface of the door around 67-68 minutes into the reconstruction (46-47 minutes after the involvement of the stairs). The door collapses (without frame) into the corridor approximately 2 minutes later (a total of approximately 70 minutes since ignition).

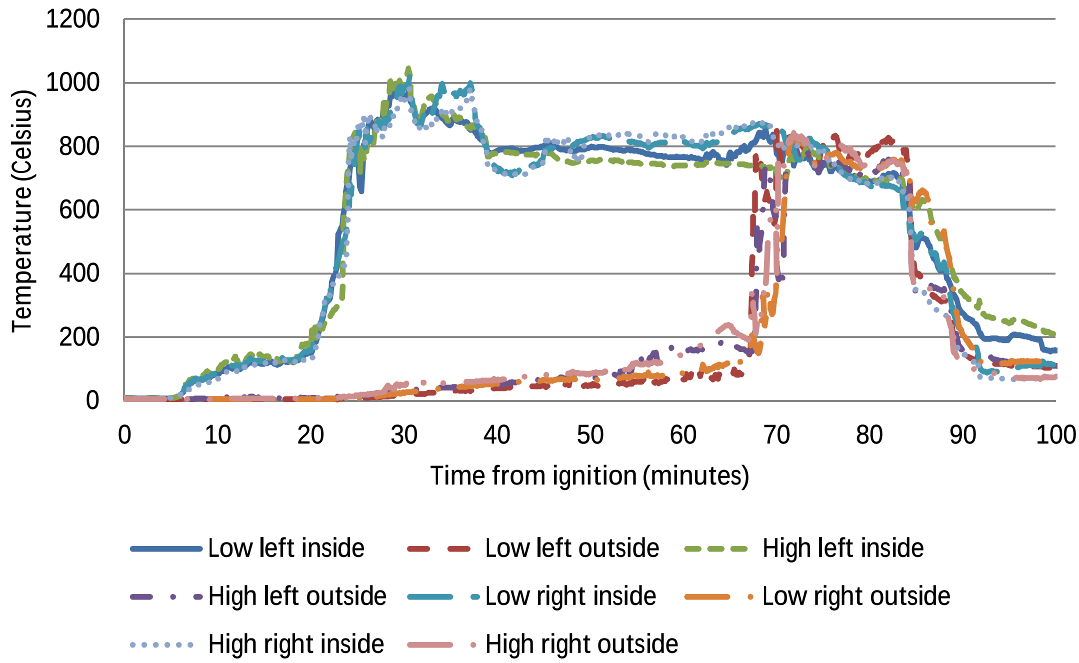


Figure 97 – Temperature data at thermocouple positions on door E[140]

Temperature data obtained from the ceramic fibreboard box beneath the stairs, Figure 98, indicate that it fails approximately 2-3 minutes following ignition of the staircase. Failure is treated as the rapid increase in temperatures at all measuring locations on the ceramic box from around 200°C to around 800°C because visual confirmation of the mechanism of failure from the video footage was not possible due to smoke logging within the suspended ceiling. This is prior to any flaming penetrating the escape door below. Temperatures at thermocouple tree F (Figure 80) above the suspended ceiling exceed flame temperatures approximately 10 minutes after this failure (34 – 35 minutes into the reconstruction). The video footage of the escape door and ceramic fibreboard box indicate well developed flaming in this area (above and below the suspended ceiling) from around 45 minutes into the reconstruction.

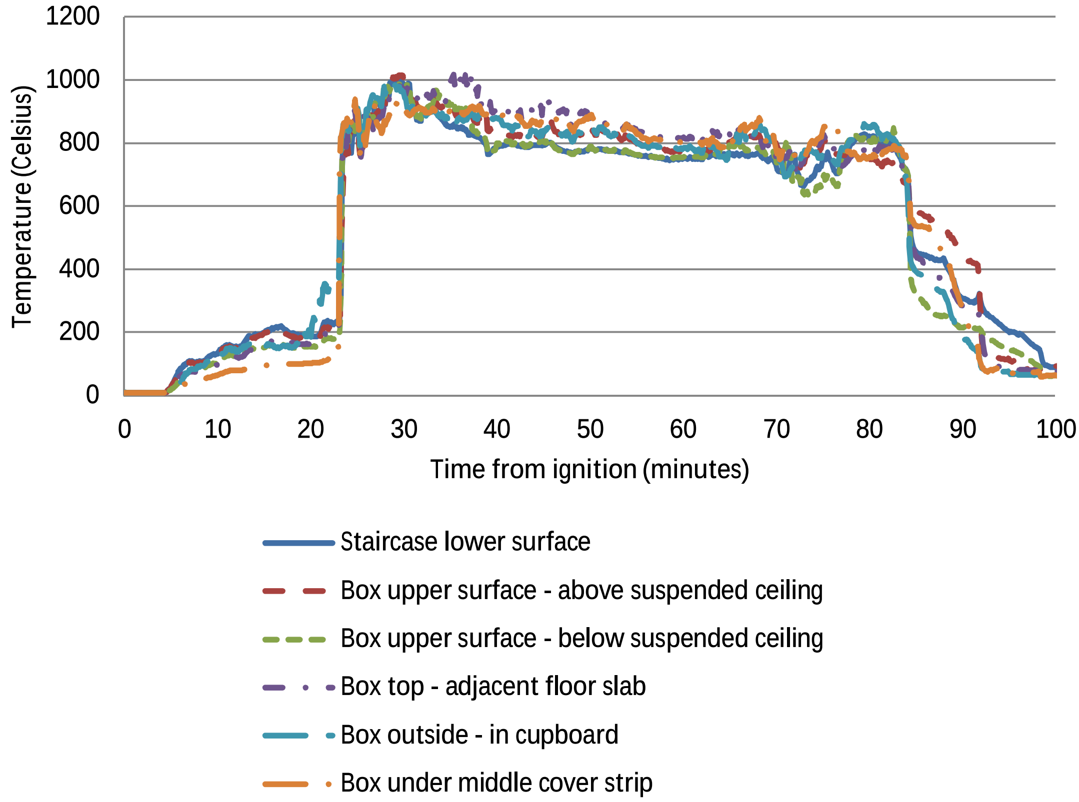


Figure 98 – Temperature data at thermocouple positions on stair box structure[140]

3.1.4.4. Data from the Heat Fluxes and Calorimeters

Of the three heat flux meters that were installed in the reconstruction rig, the corridor heat flux meter developed a fault shortly into the test. Data from the corridor heat flux meter are removed from Figure 99 for ease of viewing. Fortunately the suspended ceiling did not contribute significantly to the fire so any heat fluxes measured here would not have contributed to the analysis of the reconstruction.

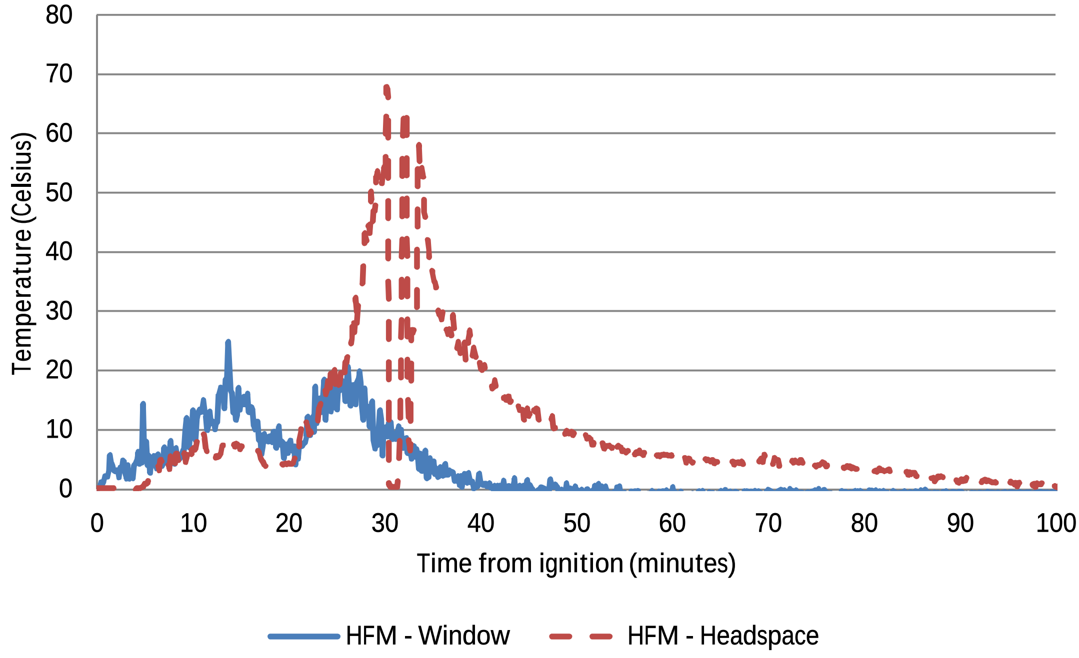


Figure 99 – Heat flux meter data from window and headspace[140]

The heat flux meter close to the windows on the upper level measured two peaks corresponding with the periods of flaming at upper level mentioned earlier. Heat fluxes here peak at around 20kW/m^2. Performance of the window panels is discussed later within the computer modelling chapter. The heat flux meter in the headspace peaks at 65kW/m^2 around 30 minutes into the reconstruction.

The calorimetry data collected from the reconstruction reflect the findings detailed so far. The peaks on both calorimeters are accounted for by the preceding involvement of significant components of the reconstruction rig. The heat release rate plots for both calorimeters are shown in Figure 100. The gas concentrations measured by the 9m calorimeter and corridor calorimeter are shown in Figure 101 and Figure 102 respectively.

Overall, the 9m calorimeter, measuring heat release from smoke exiting the window of the rig, registered two peaks of 5.0 to 5.5 MegaWatts. The corridor calorimeter peaked at close to 110 kiloWatts (0.11 MegaWatts). The difference in magnitude of these peaks highlights that the fuel load in the corridor of the reconstruction rig did not contribute to the reconstruction fire to any significant extent.

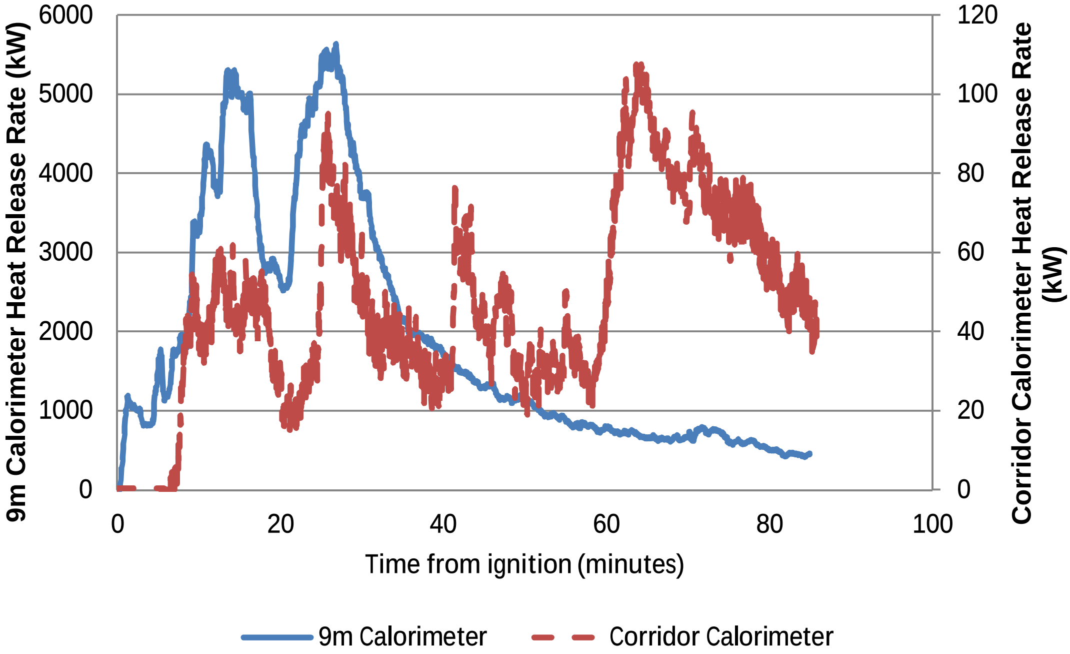


Figure 100 – Calorimetry data for the two calorimeters collecting smoke during the reconstruction fire[140]

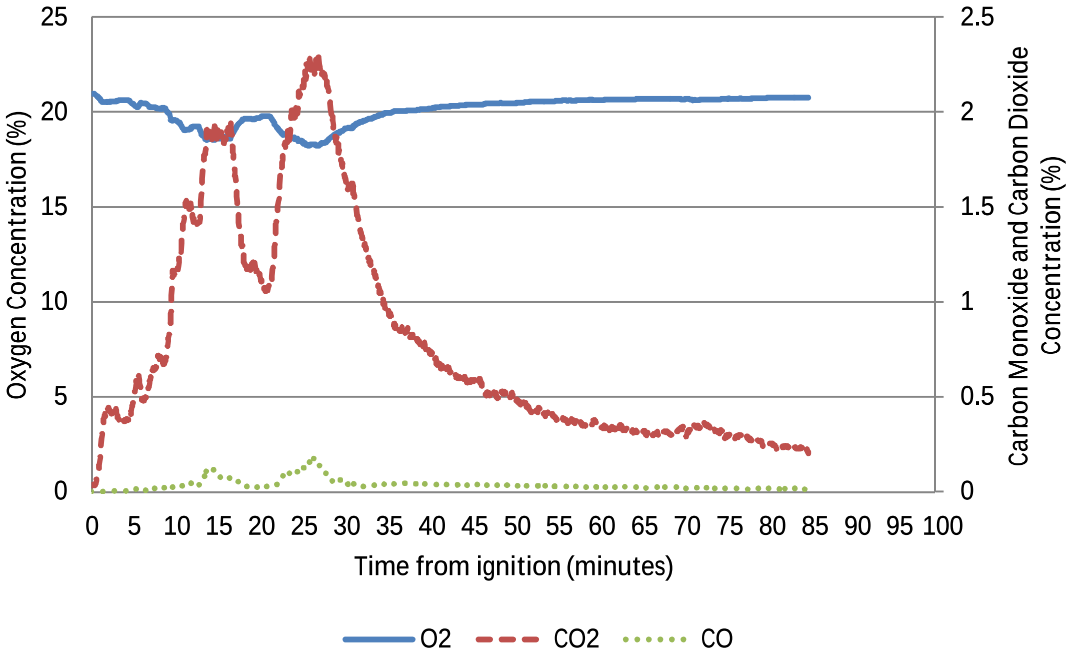


Figure 101 – Gas concentrations measured by 9m calorimeter (collecting gases from above bedroom façade)[143]

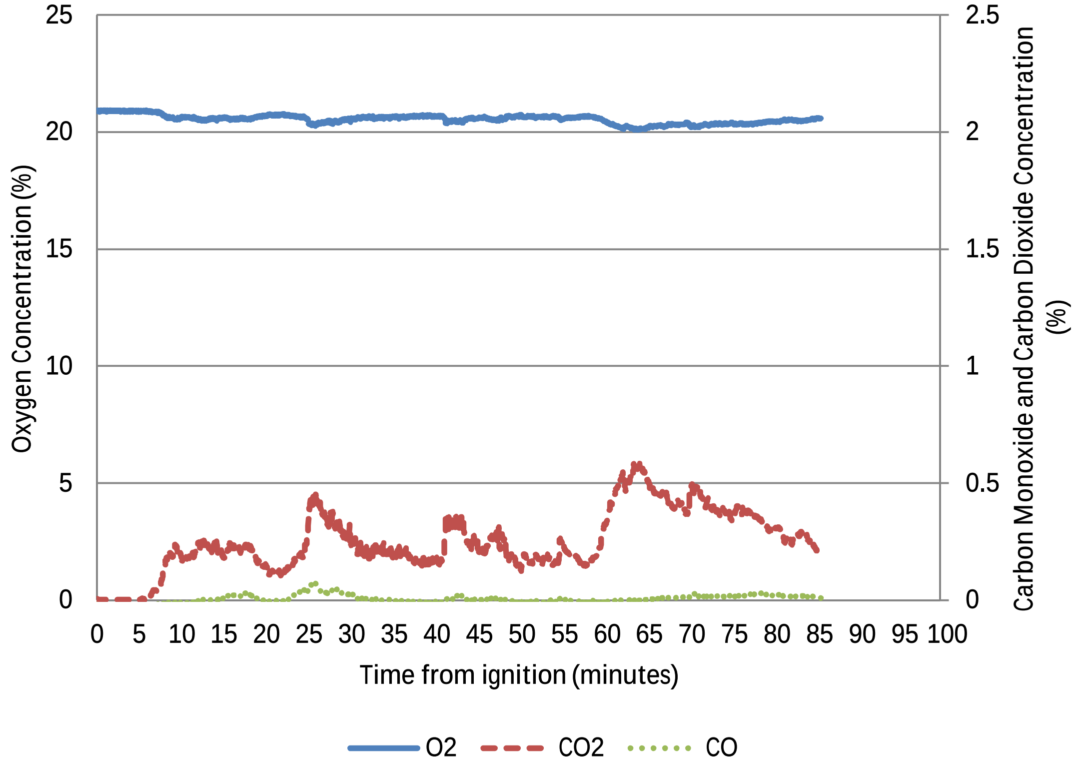


Figure 102 – Gas concentrations measured by corridor calorimeter (collecting gases from end of corridor)[143]

3.1.4.5. Data from the Gas Sampling Ports

The gas concentrations measured in the headspace (Figure 103) indicate severe conditions becoming established within 15 minutes of ignition of the reconstruction. However, as mentioned earlier, the headspace of the reconstruction rig is far smaller and has a more sealed volume than the upper floor of Flat 79. The general pattern of peaks in Figure 103 mirrors that in Figure 101 and Figure 102 but the measurements from the calorimeters are necessarily diluted by the quantity of fresh air which is entrained into the smoke that leaves the reconstruction rig.

Gas sampling of hydrogen cyanide, hydrogen chloride and hydrogen bromide was also undertaken from the headspace using bubblers for the period from 20 minutes after ignition to 35 minutes after ignition.[144] Bubblers measure a total concentration of gas for the period during which they are in operation; they do not provide continuous data. During this fifteen minute period, the average gas concentrations sampled were as follows:

- Hydrogen Cyanide: 19 ppm
- Hydrogen Chloride: 45 ppm
- Hydrogen Bromide: 3 ppm

The concentrations measured during the reconstruction reflect the restricted space that was available in the headspace compared to the space in the upper floor of a complete flat (i.e. toxic concentrations were very high and the oxygen concentration was very low).

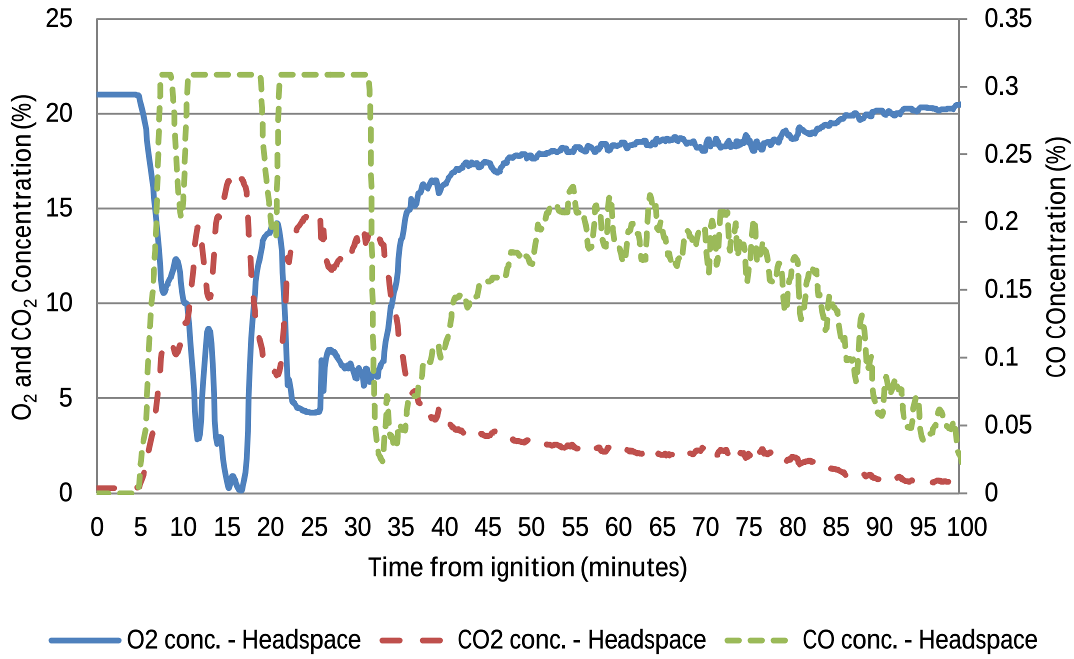


Figure 103 –Gas concentration data for gases sampled at low level in the 1st floor headspace above the stairs[140]

3.1.5. **Observed Differences between Reconstruction Fire and Incident**

As previously mentioned (see section 3.1.3) it was neither possible nor expected to fully recreate the fire that involved Flat 79 during the incident at Lakanal House.

The wind conditions for the reconstruction fire were less severe than they were during the incident. As a result, the movement of flames was more determined by their buoyancy than by the impact of any prevailing wind, as is likely to have been the case during the incident. This is likely to have meant that the fire spread less rapidly during the reconstruction than during the incident and that hot fire gases were not directed towards the corridor as much as they were during the incident. However, the reduced air movements may have also allowed higher temperatures to be attained during the reconstruction than during the incident. This is discussed in the computer modelling section (3.1.6).

The failure of the fan during the reconstruction meant that the area of high velocity flow corresponding to that passing through the security door grilles in Lakanal House was no longer present from approximately ten minutes into the reconstruction. Given the fire behaviour of the materials in the corridor (i.e. no self-sustaining ignition of the suspended ceiling structure and no self-sustaining ignition of the vinyl floor tiles), the failure of this fan is not considered to have had any significant impact upon the progression of the reconstruction fire.

The absence of bedroom 2 and the bathroom of Flat 79 in the reconstruction meant that there was less fuel available to burn and release heat to ignite the corridor and its contents. Therefore the later stages of the reconstruction (i.e. when the fire spread to the stairs and flat lobby) were probably less severe than the corresponding stage of the incident.

The window façade sets used in the reconstruction appear to have performed consistently with those involved in the incident. The window façade sets on the first floor of the reconstruction rig appear from the temperature data to have been close to ignition, evidenced by a temperature spike commencing on the interior surface of the panel immediately prior to intense flaming from the floor below ceasing. The conditions to which these panels were exposed during the incident are examined in more detail in the computer modelling section (3.1.6).

The construction of the front door of the reconstruction rig appears to have been consistent with that of the front door of Flat 65 on the 9th floor. This is evidenced by the mode of failure observed during the reconstruction and the mode of failure of the front door of Flat 65 reported by LFB during the incident. In both cases fire initially penetrated the doorset around the top of the door leaf, but much of the leaf remained intact and overall failure of the doorset was a result of failure of the ironmongery in the frame, which allowed the door leaf to fall out of the frame.

The burning behaviour of the suspended ceiling in the corridor of the reconstruction rig was not consistent with the way in which evidence suggests that the suspended ceiling of the 11th floor corridor of Lakanal House behaved during the incident. However the suspended ceiling in the reconstruction rig was only reproduced insofar as its basic timber structure, the panels making up the surface of the ceiling and a minimal number of combustible items (cabling, timber). This was to allow safe continuation of the reconstruction fire until its completion and to minimise any interference with observations of the performance of the structures separating the flat from the suspended ceiling void (i.e. the panel above the front door and the ceramic boxing in under the timber stairs).

Although necessarily not identical, the ignition source used for the reconstruction produced flames consistent in size with the size of flame tips that would be expected from a fully involved fire one storey below. This is discussed in more detail in the computer modelling section.

3.1.6. Computer Modelling Review

The fire size, rate of growth and spread observed and recorded during the reconstruction fire was intended to be mapped onto computer models and checked against the incident timeline provided by MPS and LFB. Then the reconstruction data was used to check that times obtained from the incident timeline and predicted by the computer modelling were compatible with the limitations set by the geometry of the flats of Lakanal House.

This section (3.1.6) covers the findings of work carried out by Richard Chitty of BRE (i.e. computer modelling). Full details of the work carried out can be found in BRE report number 259449[140].

3.1.6.1. Air Flow and Movements around Lakanal House

There was evidently a complex air movement pattern around Lakanal house during the incident. One of the features of the video clips of the fire incident was the movement of smoke down the west face of the building; the smoke would normally be expected to go up. This is presented in Figure 104.

Figure 104 – Smoke moving down the face of the building. Image courtesy of LFB[140]

The air flow around Lakanal House and the adjacent buildings was simulated using the CFD program CFX. Figure 105 shows vectors and streamlines indicating the predicted airflow around Lakanal House due to a wind from the west at 5.5m/s (20km/h).

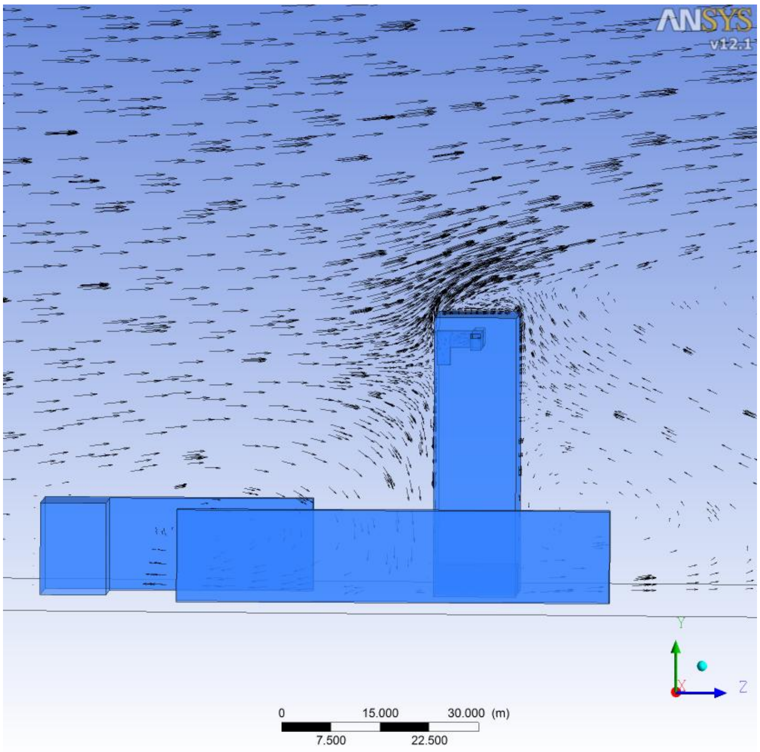


Figure 105 – Side view of vectors showing air flow around Lakanal House[140]

This simulation indicates that an airflow down the west face of the building would not be unusual when the wind comes from the west.

These simulations also included some of the internal detail of the building; the 11th floor corridor and lift lobby. This was used to provide an estimate of the airflow through the corridor in the early stages of the fire, before the barriers between the flat and corridor (doors, panels, box round stairs) failed. This flow was mainly controlled by the ventilation openings in the security doors from the corridors to the lift lobby. Figure 106 shows the air velocity along the corridor.

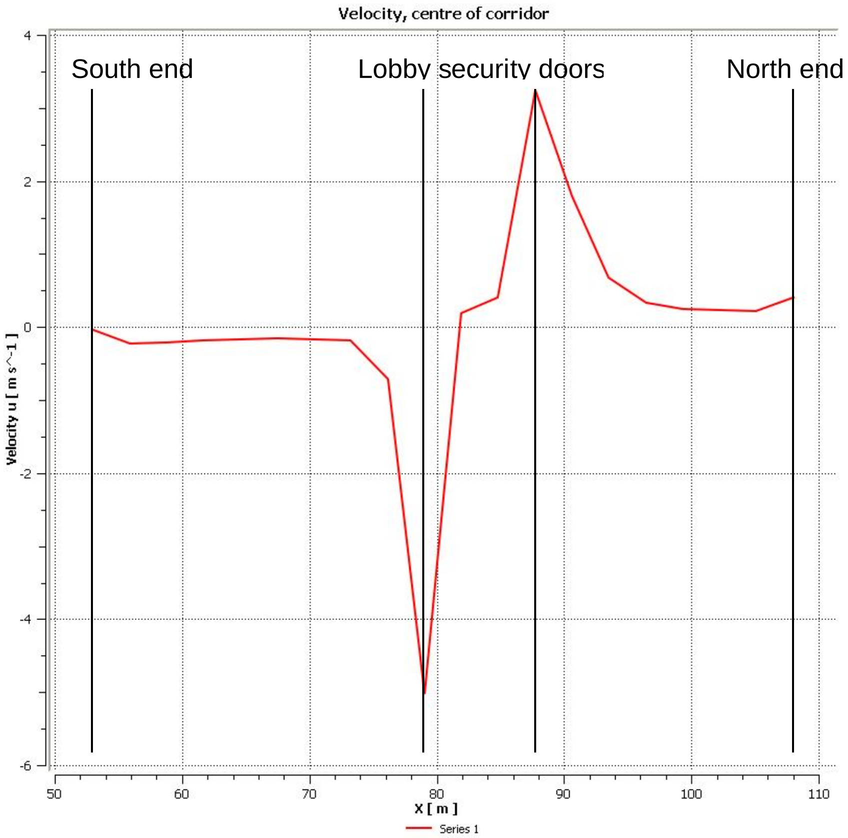


Figure 106 – Predictions of airflow along the 11th floor corridor produced by CFX software[140]

The peaks shown in Figure 106 are due to the constriction due to the grille in the security door. The average velocity in the corridor was approximately 0.1m/s. This flow rate was reproduced and the average flow along the corridor was maintained throughout the reconstruction experiment.

The CFD program JASMINE has been used to examine the effect of upward and downward airflow on the airflow on the balcony and through the flats. The simulation used a simplified representation of a flat with the kitchen door open, the windows and window panels of bedroom 1 missing and a simple opening between the levels to represent the internal stairs.

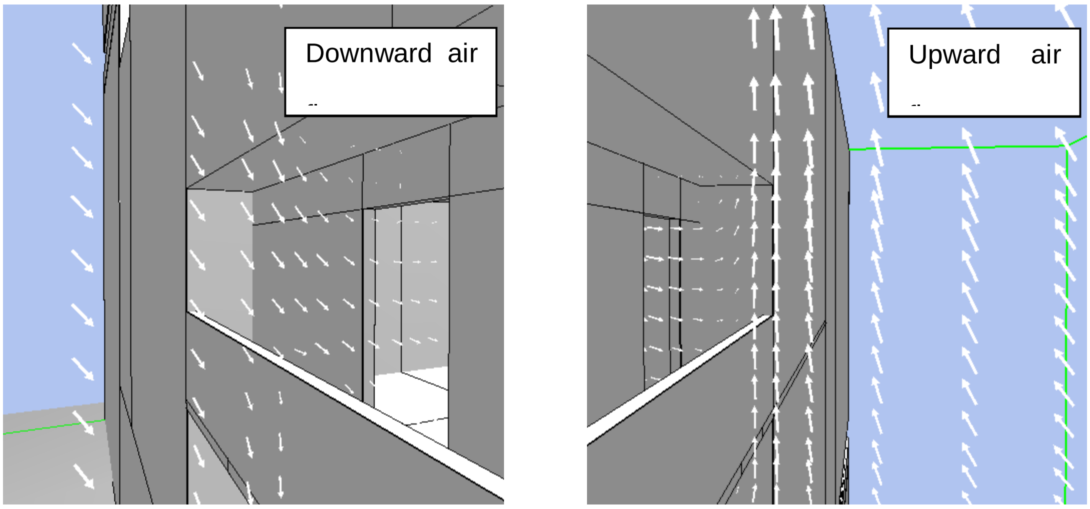


Figure 107 – JASMINE predictions of flow into flat due to wind [140]

Figure 107 shows if air is moving down the face of the building (flats on lower floors) then air will enter through the kitchen and leave from the bedroom. Conversely, if the air is moving up the building (higher floors), then air will enter through the bedroom and leave by the kitchen door.

A fire in the flat disturbs the local wind driven flow past and through the flat. A second set of simulations was run with JASMINE using the simplified geometry and including a 6MW fire in the bedroom 1 area. Figure 108 shows a mesh enclosing the volume where flames would be expected to appear (the mesh is a 300°C iso surface).

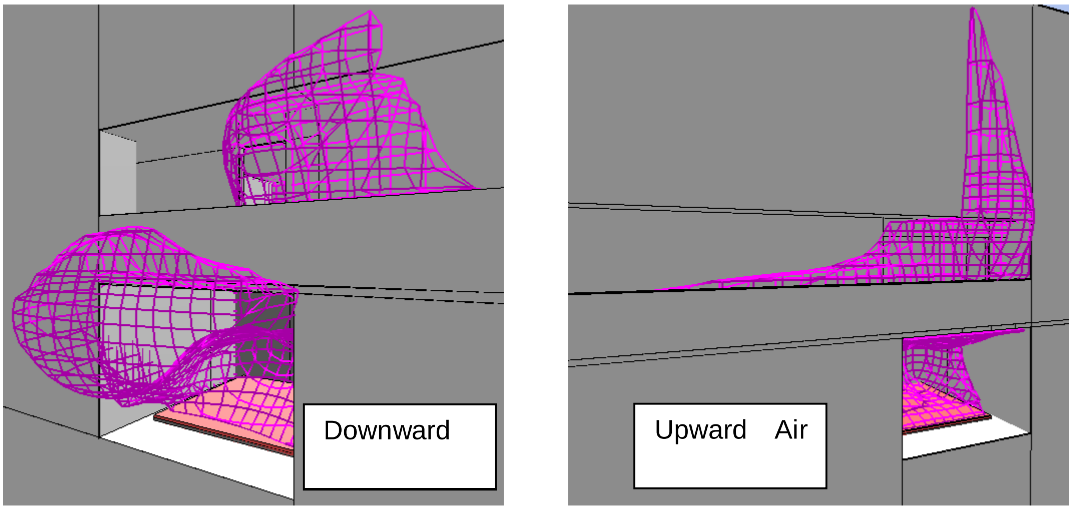


Figure 108 – JASMINE predictions of flow into flat due to wind and a 6MW fire in bedroom 1[140]

When the airflow is down the building (flats on lower floors) smoke and hot gases are limited to the balcony and are projected out of the bedroom. When the airflow is up the building most of the smoke and hot gases flow through the flat and up the outside of the building. Since the flow across the west face of Flat 65 may have been either up or down, both conditions needed to be considered in the fire simulations.

3.1.6.2. Fire Models for Flat 65 and 79

The approach has been to simulate the fire development, firstly in Flat 65 and then in Flat 79. These simulations were synchronised using established timed events from photographs and then used to provide estimates of conditions when other events would have occurred. From these results, further simulations have been conducted to estimate conditions in the 11th floor corridor and probable smoke ingress into Flat 81.

3.1.6.3. Flat 65

The fire in Flat 65 is understood from LFB and MPS to have started in bedroom 1 at a television set located near the dwarf door to bedroom 2. The right hand (as seen from inside the flat) window was fully open and the centre window in the tilt position, Figure 109.

Figure 109 – Bedroom 1 Flat 65 view of windows and location of television set[140]

From the witness statements the fire was first seen in the corner of bedroom 1 extending from the centre of the windows to the canvas cupboard (~1.5m by ~1.5 m) with flames reaching halfway up the walls. This was about four minutes after an observation when the witness entered the room to retrieve her phone and was not aware of any fire. Figure 110 shows the layout of the room (as described in statements) with the fire area shown as an orange rectangle. Statements indicate that the door to bedroom 1 is left open as the occupant evacuates.

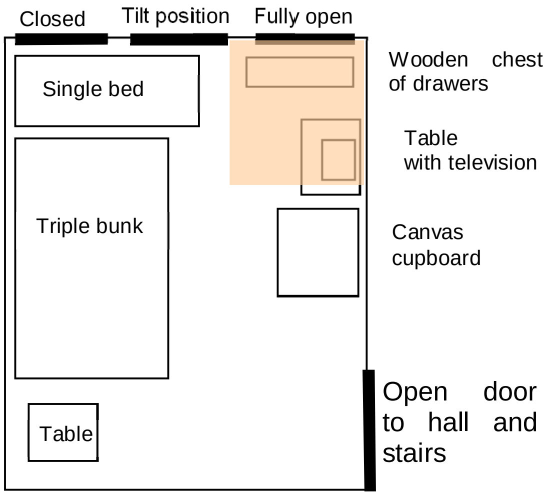


Figure 110 – Bedroom 1 Flat 65 showing location of fire when first observed[140]

A simulation was run using the simulation program, JASMINE. The sequence of events is given in Table 18**.**

	Simulation time		**Incident time (24 hour clock) calculated from modelling**
	seconds	minutes:seconds	
Established fire in Flat 65 Bedroom 1	0	0:00	***16:15:00***
Bedroom 1 window breaks	270	4:30	***16:19:30***
Partition fails	375	6:15	***16:21:15***
Bedroom 1 panel and living room windows fail	600	10:00	***16:25:00***
Flashover/backdraught in living room/kitchen	630	10:30	***16:25:30***

Table 18 – Flat 65 JASMINE simulation

Figure 111 shows the temperature predicted by JASMINE for the centre of the living room.

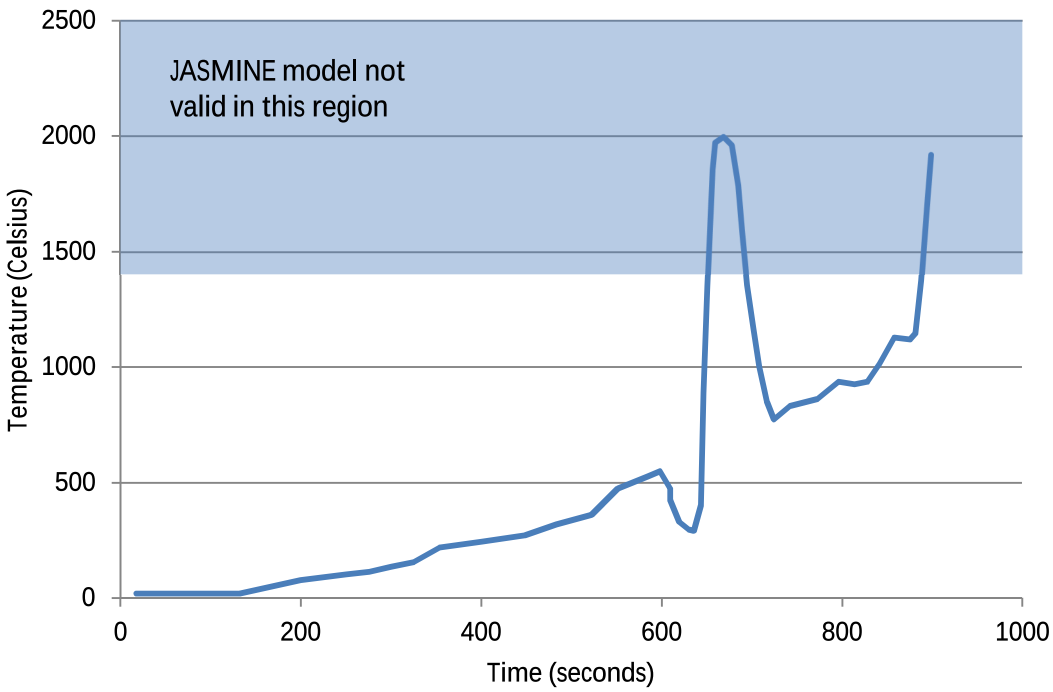


Figure 111 – JASMINE temperature predictions for Flat 65 living room[140]

When the living room window fails at 600 seconds the temperature initially drops due to fresh air coming in from outside (probably wind driven through the kitchen door). There is now sufficient oxygen in the compartment for more of the fuel from the fire to burn inside the flat and the temperature rises very rapidly. This event (a form of backdraught) and the associated temperature rise would ignite all the combustible material in the upper part of the flat (flashover) and project flames and hot gases from each side of the building.

It should be noted that the physics and chemistry used by JASMINE to predict combustion have not been validated for the severe conditions that occur after the backdraught/flashover event and the prediction of temperatures of almost 2000°C is a significant over prediction. Given that the adiabatic flame temperatures for common hydrocarbons (ethane, propane, butane) in air are in the range of 1950°C to 2000°C, such a temperature indicates that heat losses from the room are not being properly represented by the model.[145,146] Models developed for prediction of the performance of internal combustion engines would be more appropriate for this phase of the fire. The predicted temperature contours in Flat 65 are shown in Figure 112 to Figure 116.

Figure 112 – Wire frame image (i.e. wall and object outlines only) of Flat 65 used to display JASMINE simulation results[140]

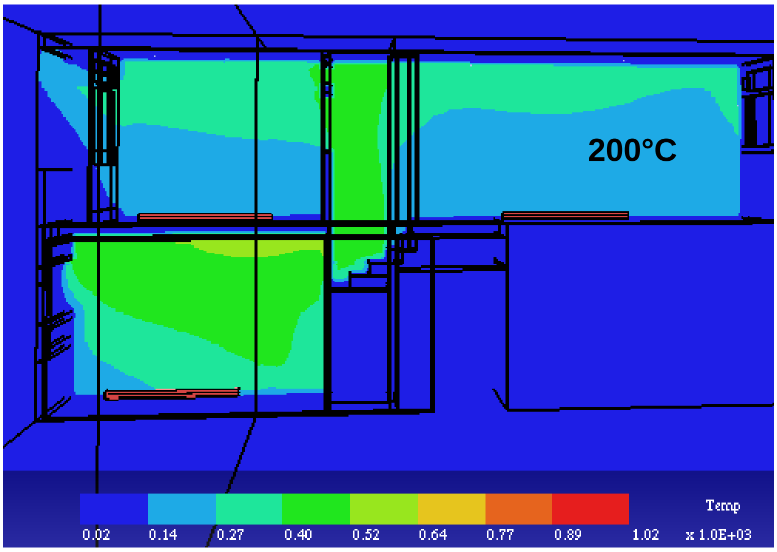


Figure 113 – Flat 65 JASMINE simulation 450 seconds[140]

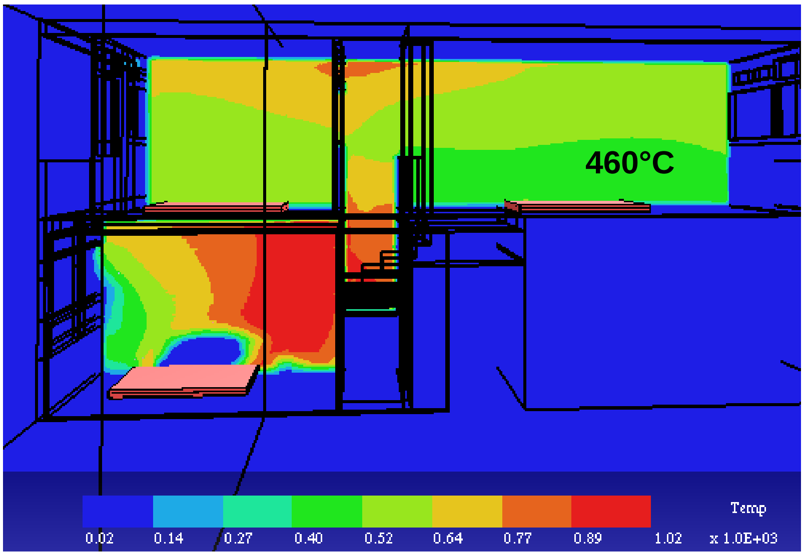


Figure 114 – Flat 65 JASMINE Simulation 600 seconds[140]

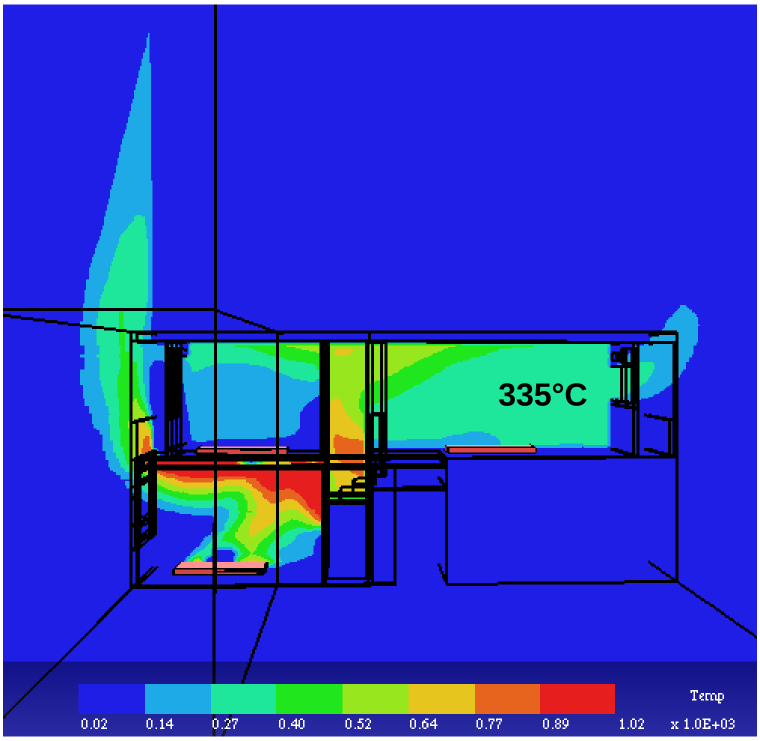


Figure 115 – Flat 65 JASMINE simulation 640 seconds[140]

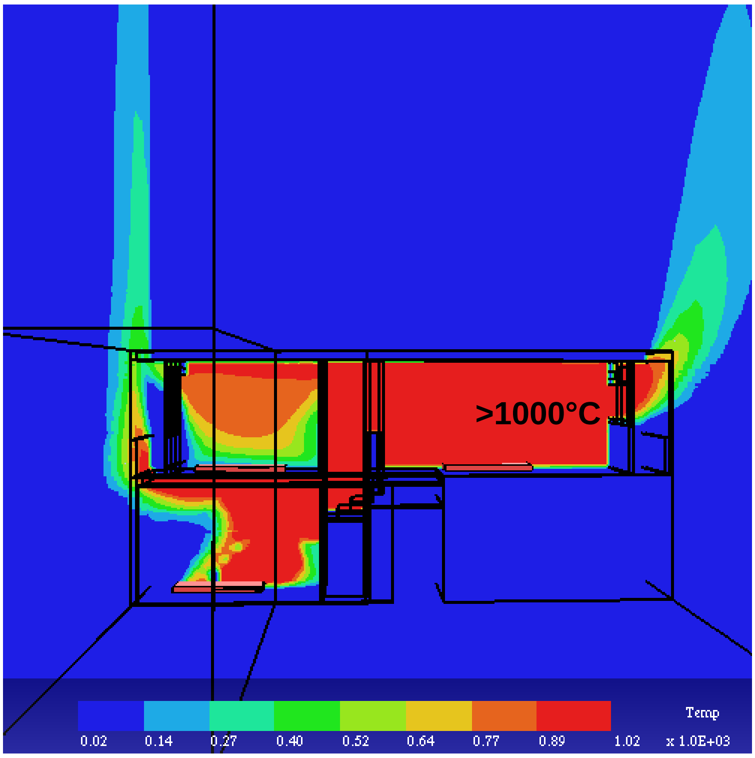


Figure 116 – Flat 65 JASMINE simulation 700 seconds[140]

Immediately after the rapid development of the fire (at approximately 16:25) flames would be projected from the kitchen window/door and up the face of the building across the window panels of Flat 79.

3.1.6.4. Flat 79

The fire in Flat 79 started when external flaming from Flat 65 below ignited, or caused to distort, the panel in the bedroom 1 window. At 16:23 the occupant of Flat 79 observed smoke through the floorboards and heard “crackling” at 16:26, which corresponds with the rapid development of the fire in Flat 65 above. The occupant of Flat 79 closed all the windows and doors.

As Flat 79 was only open on the lower level (due to the failure of the window panels and, later, the windows) there was no wind driven airflow through the flat. Therefore, the upward and downward ventilation scenarios considered for Flat 65 do not need to be included for Flat 79. The penetration of fire into Flat 79 and its subsequent development was the scenario represented by the reconstruction.

All the windows in Flat 79 were initially closed and ventilation to the initial fire in bedroom 1 was provided by removing one of the window panels (to simulate the fire penetration from Flat 65 below). The sequence of steps in the simulation using the JASMINE program, is given in Table 19.

Event	**Simulation time**		**Incident time (24 hour clock) calculated from modelling**
	seconds	**minutes:seconds**	
“Flashover” in Flat 65	N/A	N/A	***16:25***
Fire enters Flat 79	0	0:00	***16:30***
Windows break	270	4:30	***16:34:30***

Table 19 – Flat 79 JASMINE simulation

In Flat 79 the internal partition between the kitchen and living room had been removed and the temperature in the upper level did not reach the temperature criteria used here for windows to break (windows in the upper floor of Flat 79 were intact when found by fire fighters, see section 3.1.1); consequently, the fire did not receive additional ventilation and develop suddenly as in Flat 65.

Figure 117 and Figure 118 show temperature distributions in Flat 79 at 300 seconds and 500 seconds from ignition of an established fire in bedroom 1. Figure 119 plots the temperature in centre of the living room at floor, middle and ceiling level.

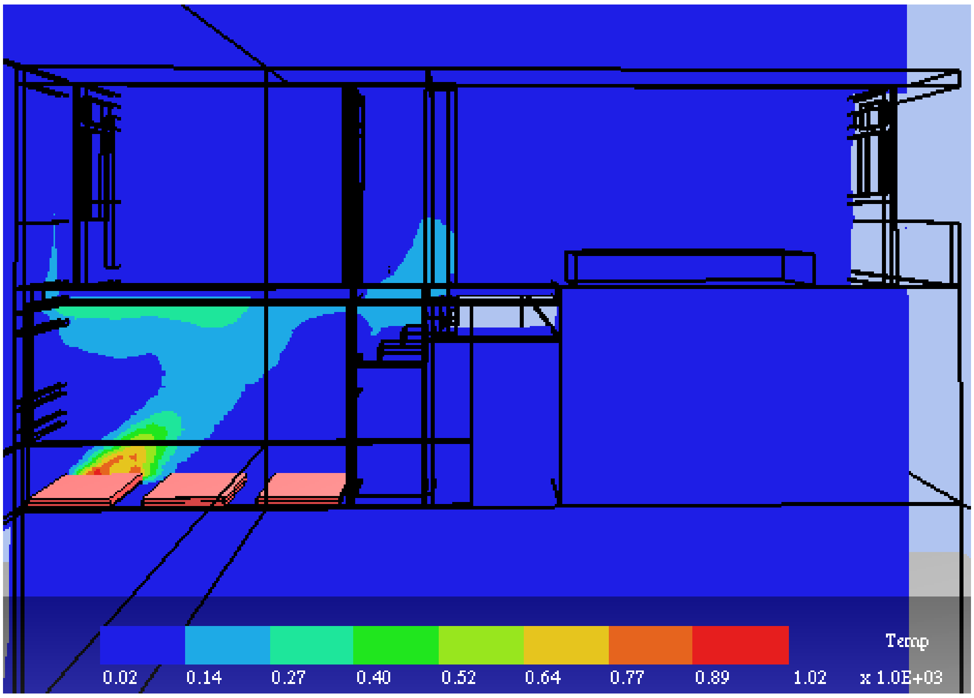


Figure 117 – Flat 79 JASMINE simulation 300 seconds[140]

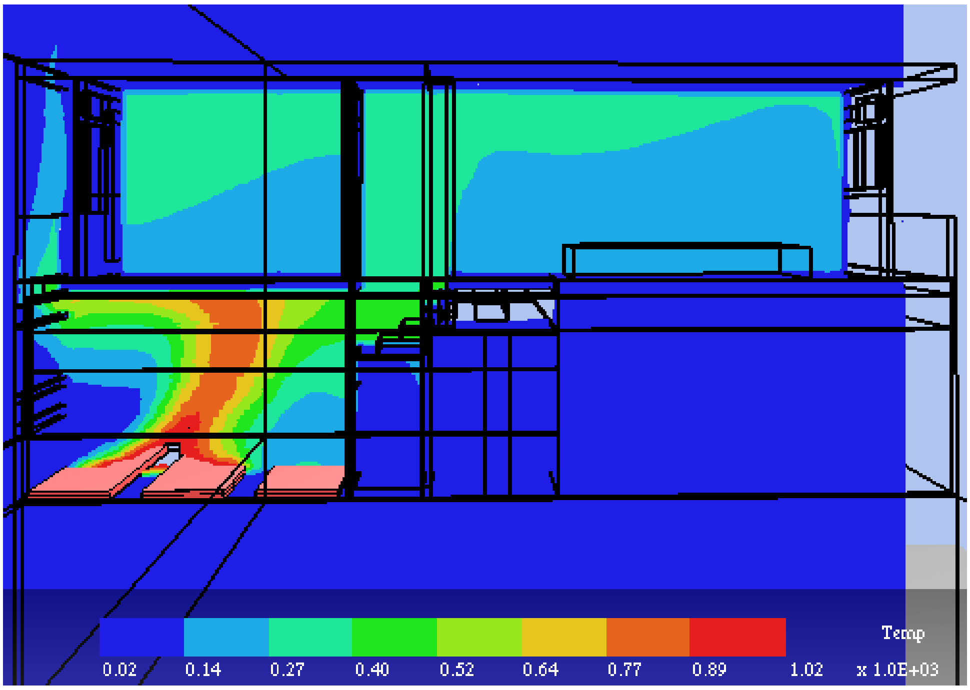


Figure 118 – Flat 79 JASMINE simulation 500 seconds[140]

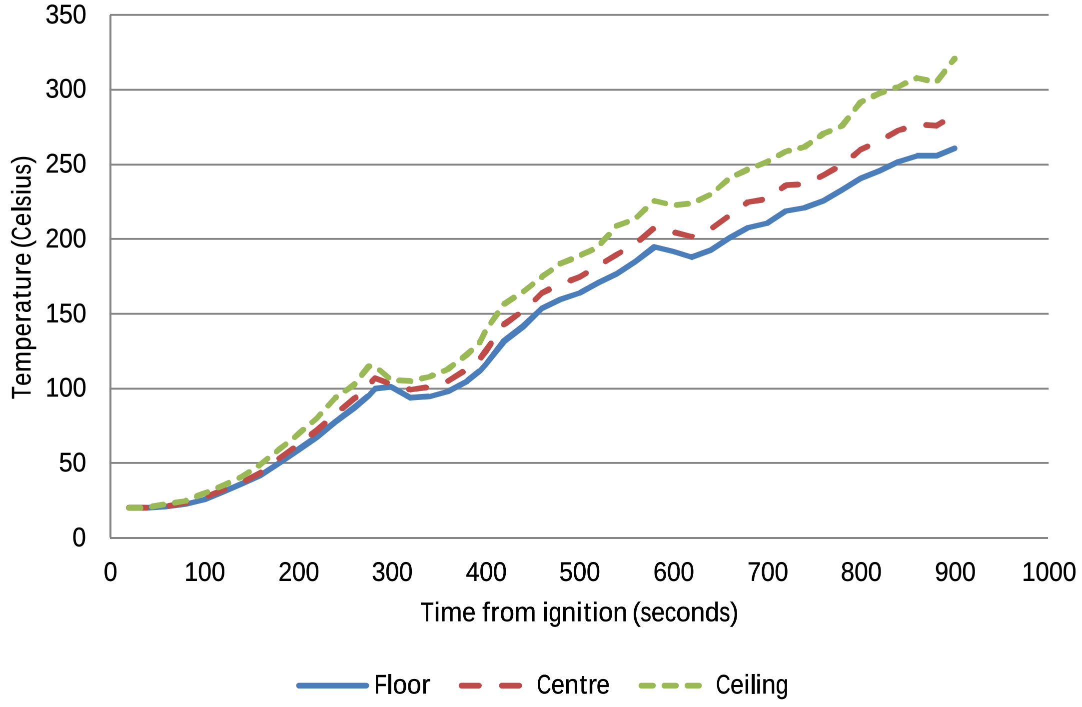


Figure 119 – Flat 79 JASMINE simulation temperatures[140]

3.1.6.5. Fire Spread from Flat 65 to 79

Figure 120 shows the west elevation of Flats 65 and 79 during a gust of wind, which had temporally cleared the smoke. At this time fire fighting had just started in the lower floor of Flat 65. The outer panes of glass in the windows of bedroom 1 and bedroom 2 of Flat 79 are broken indicating exposure to a significant quantity of heat. The window panel in Flat 79 bedroom 1 has either burnt away or fallen away as a result of loss of the panel's structural rigidity due to burning. The balcony panel opposite the kitchen of Flat 65 is in place and shows some smoke staining and blistering, but less damage than to the windows and panels of Flat 79 bedroom 1. This suggests that the flaming that caused the damage to Flat 79 came from the upper level (kitchen) of Flat 65 and not the lower level (bedroom 1).

The JASMINE simulation of the fire in Flat 65 indicates that the rapid development of the fire in the upper level of Flat 65 following windows breaking in the living room or kitchen would lead to extensive flaming over the window panel of Flat 79.

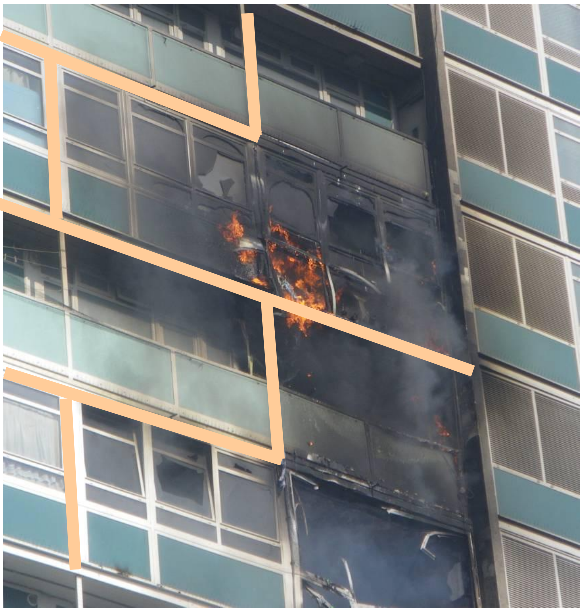


Figure 120 – IMGP5569 (cropped) taken at 16:41:05[140]

There is still a significant fire in the kitchen or kitchen balcony of Flat 65; the source of fuel may be the freezer in the kitchen of Flat 65 and/or the panel to the side of the kitchen door.

3.1.6.6. 11th Floor Corridor

Smoke entering the corridors and stairwell during the early stages of the fire while occupants were evacuating was probably due to wind blowing smoke from Flat 65 (and later Flat 79) back into the building through the ventilation grilles on the central access shaft, Figure 121 shows smoke staining of these grilles.

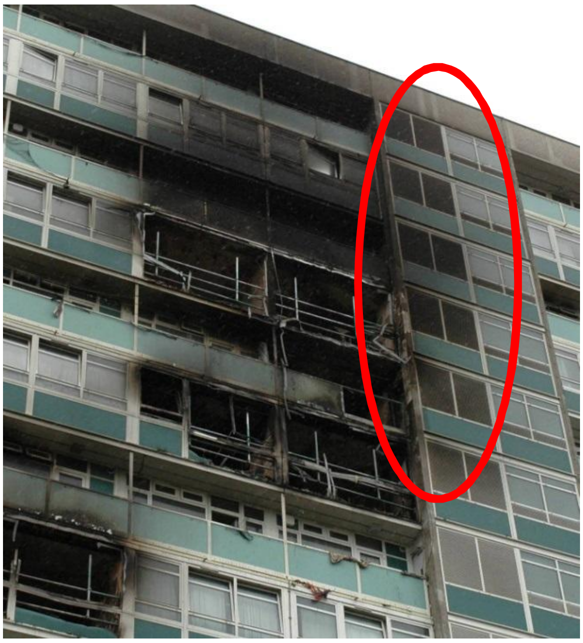


Figure 121 – Post fire image showing smoke staining of ventilation grilles[140]

At a later stage of the incident, smoke and hot gases from burning flats were able to enter the corridors, principally the North section of the 11th floor corridor from Flat 79, when either the door, door panels or box around the stairs failed. The data from the reconstruction provides some indication of the severity of the conditions here, but the effect of the prevailing wind on the severity of conditions is also considered by the modelling.

JASMINE simulations have been performed to predict the consequence of openings occurring between Flat 79 and the corridor. These simulations include the details of the Flat 79 and assume that the fire involves both bedrooms. The effect of wind is also included.

The geometry of the corridor and ceiling void is shown in Figure 122. The left image shows the doors to Flat 79 (in blue with the opening representing the security grill in the lobby door at the end of the corridor). The right image is viewed from inside the ceiling void. The "wireframe" shows the location of a block representing some of the pipes and other obstructions in the void; the yellow object is at the location of the internal stairs the flat passing through the floor slab.

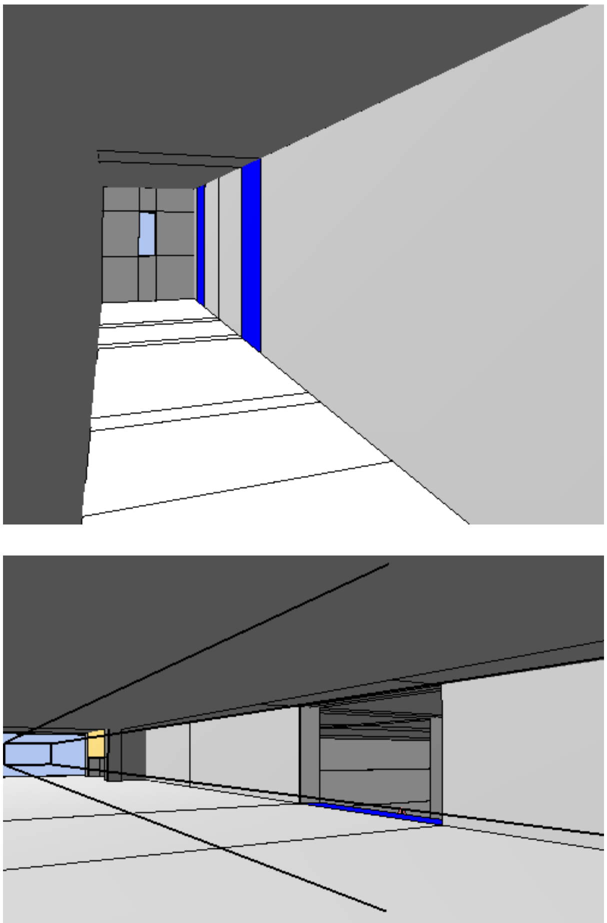


Figure 122 – JASMINE model of corridor and ceiling void[140]

The JASMINE simulations predicted an airflow of 6.9kg/s ($20m^3/s$) through the open door into the corridor. These gases have a predicted average temperature of 780°C and an average oxygen concentration of 14% (by mass). Figure 123 shows the distribution of temperature at three heights in the corridor with an open door to the flat. On the north side of the door, the flow is like a pipe flow along the corridor, the drop in temperature is due to heat losses to the corridor walls. On the south side, there is some stratification with the temperature increasing with height. Figure 124 shows a contour map of the temperatures in the corridor.

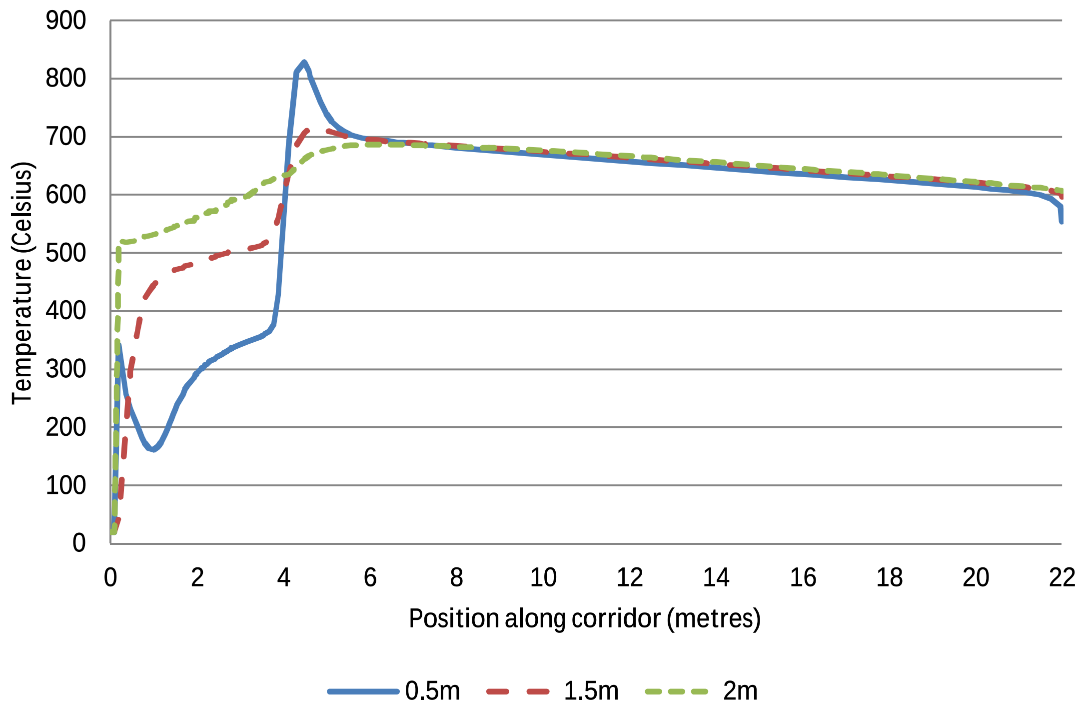


Figure 123 – JASMINE simulation of corridor and ceiling void [140]

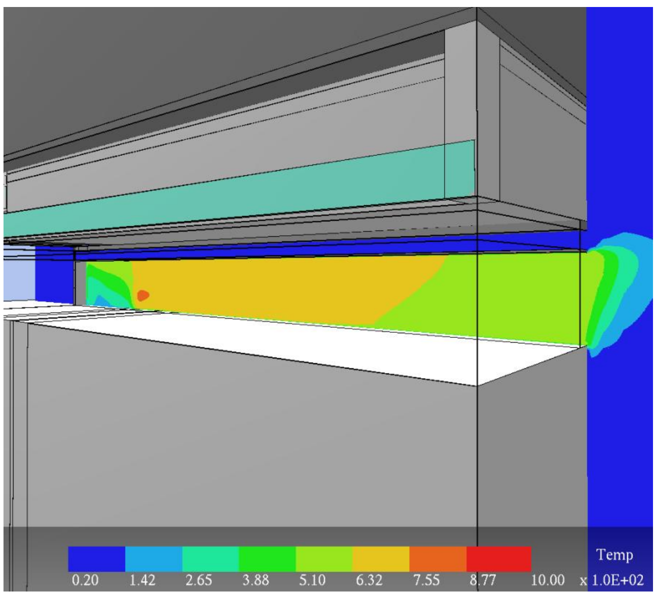


Figure 124 – JASMINE predicted temperature contours in the corridor [140]

The high temperatures (> 600°C) indicate flaming along the length of the corridor. Figure 125 is an estimate of the radiative heat flux intensity to the surfaces of the corridor along its length assuming the front door is removed from Flat 79. The intensity, I, in kiloWatts per square metre, is calculated using the formula for radiant heat flux from a black body emitter:[18]

$$I = \sigma\varepsilon\varphi T^4 \tag{10}$$

Where:

T is the absolute temperature of the gases

s is the Stefan Boltzmann constant (5.67e^{-11} kW/m^2/K^4)

e is the emissivity (assumed to be 1 as the flames are thick and the fire underventilated)

f is the view factor (assumed to be 1 as the flames are in contact with the walls of the corridor)

There would also be convective heat transfer to the surfaces of the corridor and this would add additional heat to the materials.

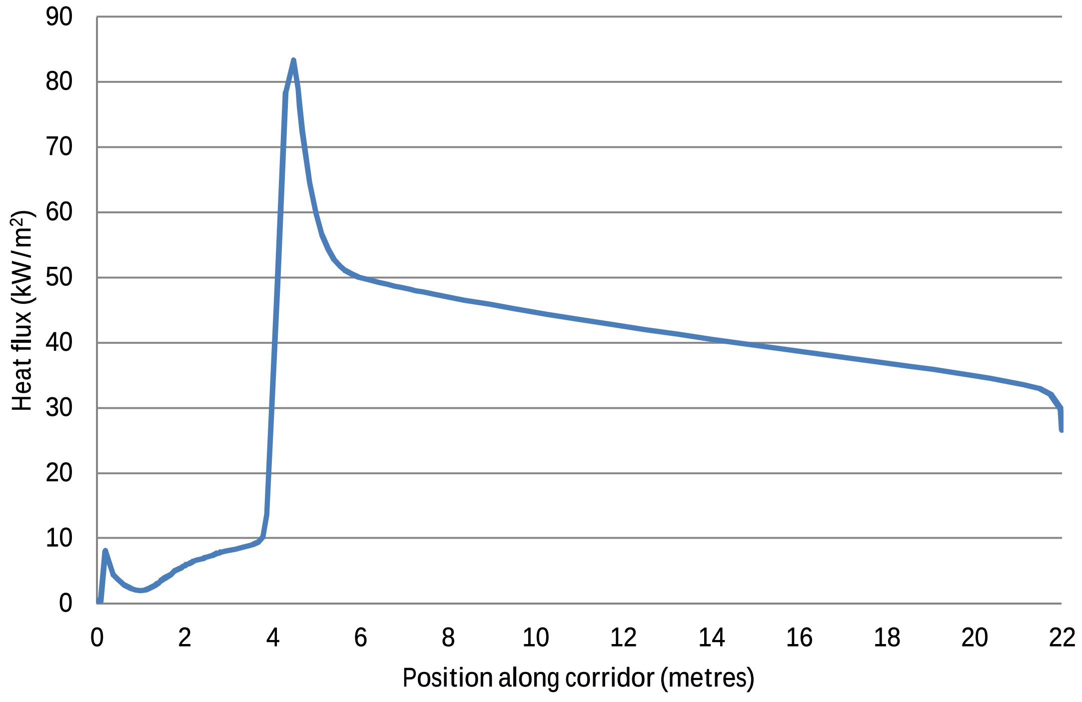


Figure 125 – Heat flux to surfaces in 11th floor corridor[140]

It should be noted that a heat flux of 12.6kW/m^2 will enable the ignition of wood after 10 minutes exposure in the presence of a pilot flame. (This criterion is used for the separation of buildings.) A heat flux in excess of 25kW/m^2 will result in spontaneous ignition of most combustible materials after a few 10's of seconds. For comparison, sunlight on a hot day in the UK is approximately 0.4kW/m^2.[147] Figure 125 indicates that all the combustible surfaces along the length of the 11th floor corridor would ignite spontaneously after the door to Flat 79 was opened.

Figure 126 shows the air speed in the centre of the corridor reaching 14m/s near the open door (~30mph). The flow has to turn through a right angle into the corridor, which creates a lot of turbulence and would be noisy. In addition, the flow of gases through the door would contain both unburnt fuel and oxygen. In some locations these may form a mixture close to the stoichiometric ratio (an ideal mixture), which would burn with a bluish flame. This can be compared to increasing the air supply on a Bunsen burner to change from a lazy yellow flame to a roaring blue flame. The flow of hot gases leaving Flat 79 into the corridor is show in Figure 127.

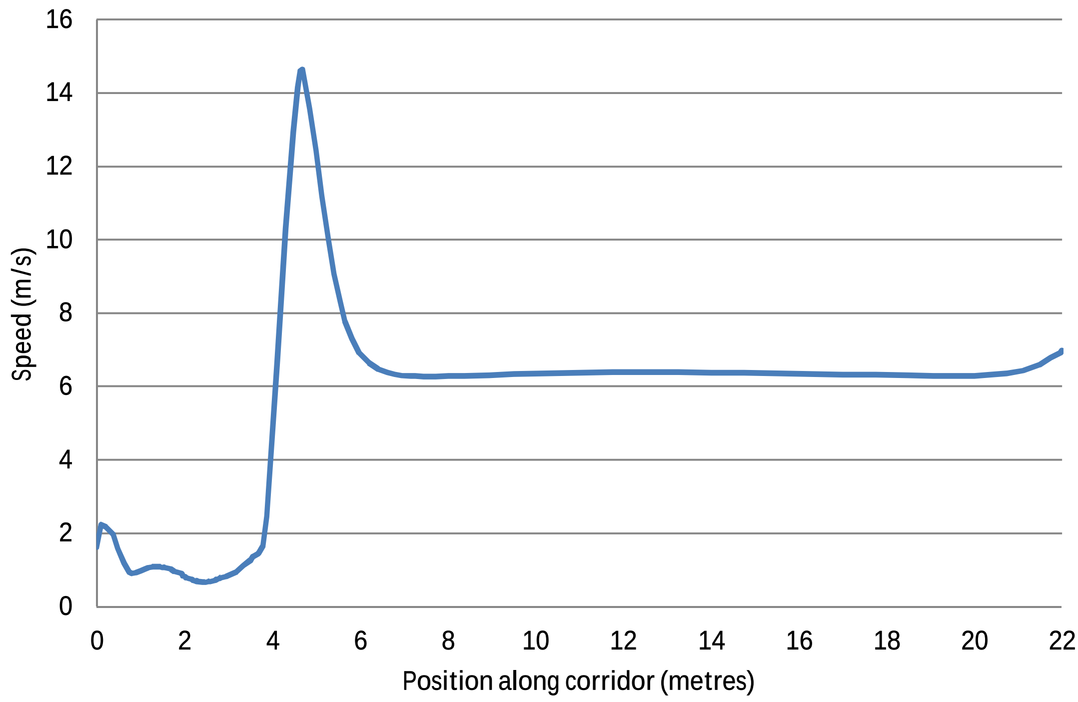


Figure 126 – Air speed in corridor[140]

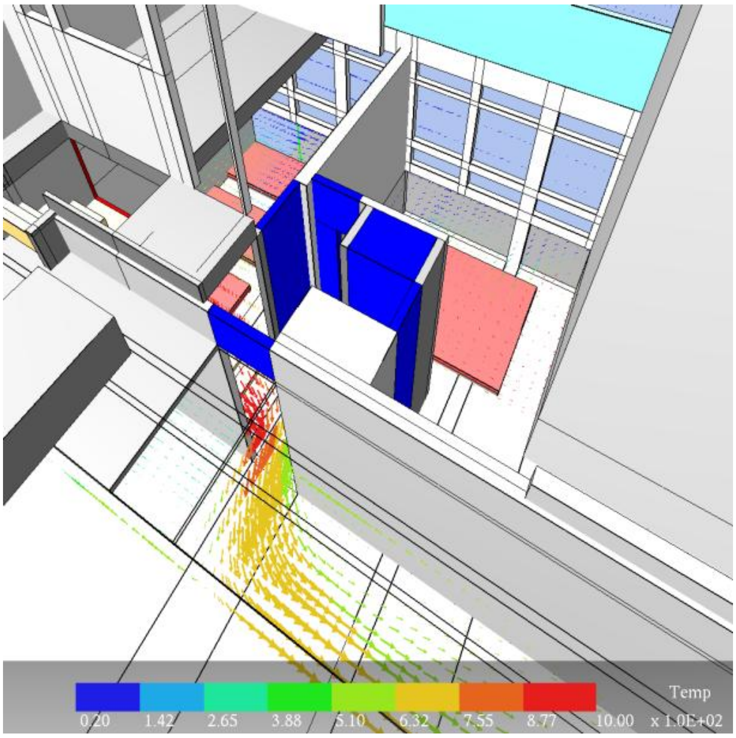


Figure 127 – Flow of hot gases into the corridor[140]

In Figure 127 the direction of the arrows indicates: the direction of the flow, the size of the arrow the gas speed and the colour the temperature of the gases. Figure 128 shows the temperature of hot gases in the void above the false ceiling of the corridor (on the east and west sides of the void – Lakanal is oriented in a north/south direction), assuming the panel above the door has failed and that the void is sealed.

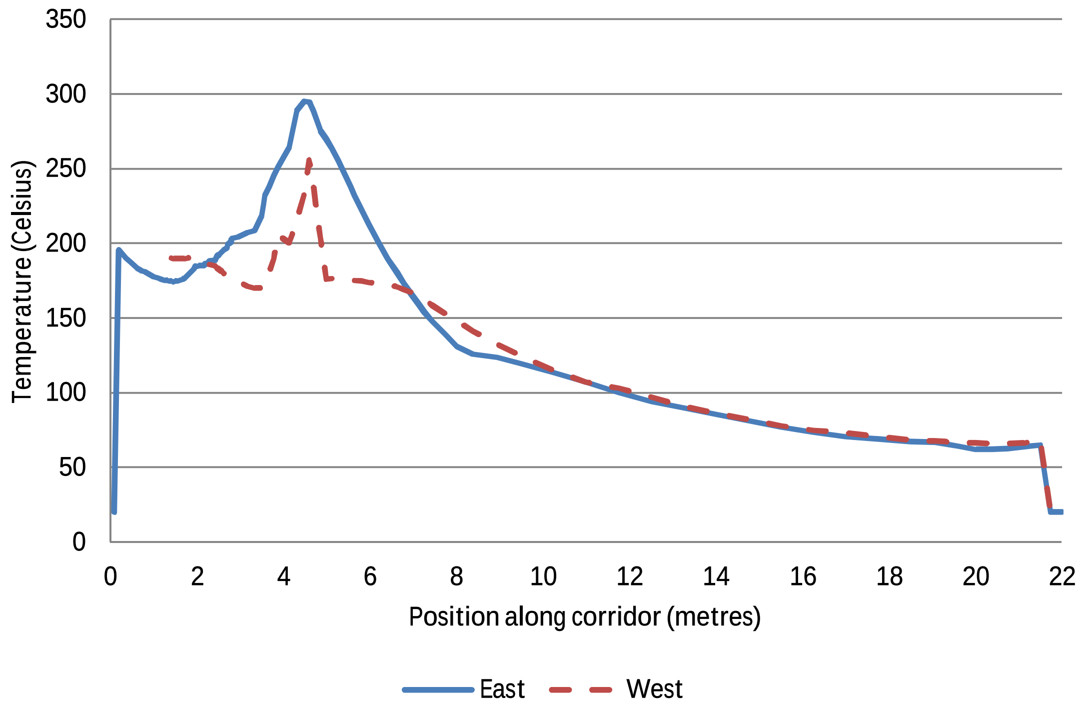


Figure 128 – Temperature above the false ceiling[140]

These temperatures are much lower than the case where the door opens into the corridor as there is no flow through the void and the hot gases remain close to the opening. These temperatures are high enough to indicate intermittent flaming (>300°C) which may ignite thin items e.g. paper or some insulation materials (tinder), which could then ignite more substantial items. However the availability of oxygen in the void would soon limit the total size of the fire in that space.

The computer modelling and data from the reconstruction has provided some indication of the time at which the fire spread into the 11th floor corridor (circa 17:05 to 17:40) but these should not be relied upon in favour of actual evidence from the incident. Photographs taken by LFB during the incident, including Figure 52, have been used to confirm and refine the calculations, ultimately providing a time close to 17:20 when the compartmentation between Flat 79 and the corridor was breached.

3.1.6.7. Fire Load and Heat Release Rate in the 11th Floor Corridor

Bureau Veritas UK was commissioned by London Fire Brigade to measure the accumulated thickness of paint in the corridors and estimate the contribution the paint would have made to the fire in the 11th floor corridor (north).[148]

The report estimates that the paint would contribute 2016MJ to the corridor fire load. To illustrate the impact of this material in well ventilated conditions; it could burn for 10 minutes with an average heat release rate of 3.4MW or for 15 minutes with an average heat release rate of 2.2MW.

Bureau Veritas UK also estimated the fire load contributed by the ceiling panels as 3110MJ (assuming the panels burn to ¼ of their thickness). This can be illustrated as a 5.2MW fire burning for 10 minutes in well ventilated conditions.

Bureau Veritas UK found that the layers of paint included at least one fire resistant ("fire upgrade") layer that may have affected the rate of heat release from the paint. Bureau Veritas UK indicates that this effect is not quantifiable. In addition, it should be noted that the 11th floor corridor contained 12 doors (6 front doors and 6 "Fire escape" doors) of various types of construction, which contributed to the fire. Based on a charring rate of 0.4mm/minute, a thickness of 35mm, a wood density of 800kg/m^2 and a heat of combustion of 18MJ/kg if the whole door surface was involved then, if the fire was not ventilation controlled, the heat release rate from each door would be 200kW. This could continue for 75 minutes to reduce the door thickness to 5mm. This assumes that the door is exposed to an average heat flux of 35kW/m^2, typical of a furnace test. If the intensity was higher, then the heat release rate would increase and the duration decrease.

With all the doors, paint and ceiling surfaces burning along the 11th floor corridor, and if there was a free supply of air, then the total heat release rate could reach 11MW (assuming the paint and ceiling material burnt for 10 minutes). This is without any contribution from Flat 79.

The airflow into the 11th floor corridor was however controlled by the size of the openings into the corridor. The simulations described above show that for an open door (i.e. after the failure of the door to Flat 79) the flow rate of air into the corridor was 7kg/s. This air had passed through the fire in Flat 79 and would have had lower oxygen content (14% by mass) than fresh air (23% by mass). Assuming that burning material in the corridor reduces this to 5% then the rate of consuming oxygen in the corridor would have been 0.6kg/s. Since most hydrocarbon materials burn consuming oxygen at a rate of 13MJ/kg[149], this would limit the heat release rate in the corridor to 8MW. Hot unburnt fuel would burn outside the vent at the end of the corridor when it reached the oxygen in the open air.

Gusting wind may also have increased the airflow, and hence the fire heat release rate for short periods allowing the heat release rate of the fire to become close to the fuel controlled limit of 11MW.

Opening the security door by fire fighters fighting the fire would allow additional air to enter the corridor. However, the fire fighters' bodies would obstruct this additional flow of air. This, together with the fire fighting actions, would make any estimate to the change in the fire heat release in the corridor very speculative.

3.1.6.8. Flat 81

The spread of smoke and hot gases into Flat 81 has been considered in two phases; before and after a family of four left the flat at approximately 17:06 (there were initially nine people in the bathroom of Flat 81). In the early phase, smoke entered the flat through various leakage paths. In the later phase, a fire was established in the 11th floor corridor (see section 3.1.6.6), the ceramic board box failed, allowing the fire to involve the stairs and spread into the flat. The fire here was confined to the area immediately around the point of penetration and limited by the availability of oxygen in the flat.

Flaming would only have occurred in Flat 81 on the stairs and possibly around the front door. Smoke would have entered the flat through several routes from other parts of the building at different times during the incident. In the early phase, smoke could enter the flat through routes from fires in other flats. In the later phase, when the fire was established in the 11th floor corridor, the ceramic board box failed, allowing the fire to involve the stairs and spread into the flat. The fire here was confined to the area immediately around the point of penetration and limited by the availability of oxygen in the flat. This would have had a significant impact of the tenability throughout Flat 81.

3.1.6.9. Smoke in Flat 81 prior to 17:06

There were several potential routes for smoke to enter the flat:

- Through the windows and external doors
- Through the bathroom ventilation system
- From the corridor, through service openings or door gaps.

The windows were closed by the occupants apart from a short interval when one attempted to attract attention by calling out of the bedroom 1 window. Post fire photographs (DSC0102, see Table 15) show the window in bedroom 1 was cracked as a result of the fire in the adjacent flat (Flat 79) and this led to minor smoke staining around the corner of the window. There was also some smoke near a trickle vent however this does not appear to be a significant path for smoke ingress into Flat 81. Other windows and external doors to the flat were closed during the incident except for brief periods when occupants of Flat 81 went in and out.

The bathroom of each flat in Lakanal House is provided with a ventilation extract point. The extracts from each flat join a common duct with the flats above and below. These ducts lead to the roof where they join in a manifold, which leads to a large fan in a plant room. See Figure 129.

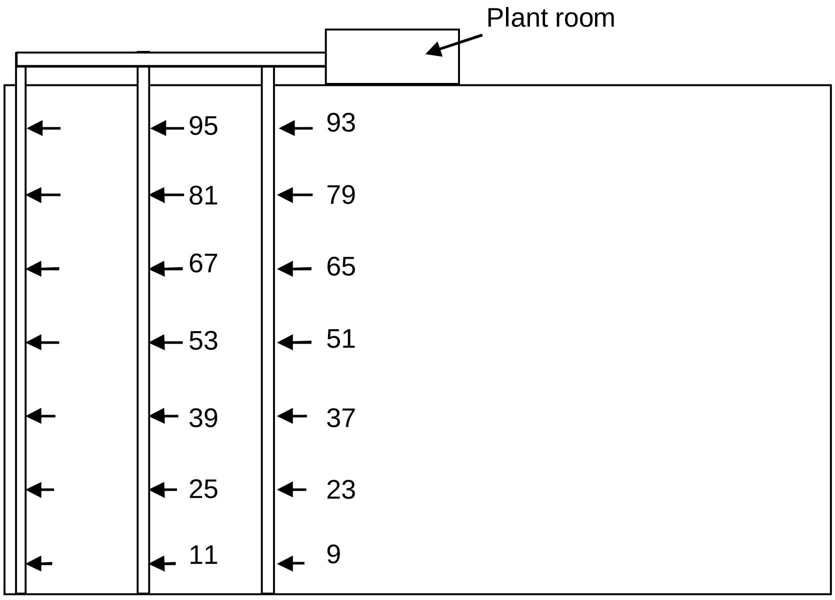


Figure 129 – Network of ventilation ducts viewed from same side of building as Figure 50 (West face) [140]

Assuming the extraction system was designed to extract three air changes per hour from each bathroom (1972 Building Regulations P3 (4)(b)[150]) then the designed extract rate for each bathroom would have been be 1.5 x 2 x 2.5 x 3 = 22.5m^3/hour = 6.25L/s. Therefore the total flow in each "leg" of the ventilation duct network should have been 7 x 6 = 42L/s. The precise value will be dependent on how the legs of the duct system are balanced. The total capacity of the plant room extract fan would therefore be expected to be at least 90 (flats) x 6.25 = 560L/s (~0.6m^3/s). Make-up air for each bathroom came from within the flat, possibly intended to pass under the bathroom door.

As seen in Figure 129, Flat 81 is linked to Flat 53 by a vertical duct and this provides a potential route for smoke and hot gases to move between the flats. In addition, a potential further route for smoke spread into Flat 81 is from Flats 37, 65 and 79 via the main roof duct. Figure 130 shows a "standard" bathroom grille leading to the ventilation ductwork.

Figure 130 – "Standard" ventilation grille (taken in Flat 67)[140]

Figure 131 shows the duct behind the grille leading to a damper and the vertical duct.

Figure 131 – Duct and damper behind the grille[140]

Figure 132 shows a cross section of the junction between the ducts and the location of the dampers. The gap (A) was measured and these values are given in Table 20.

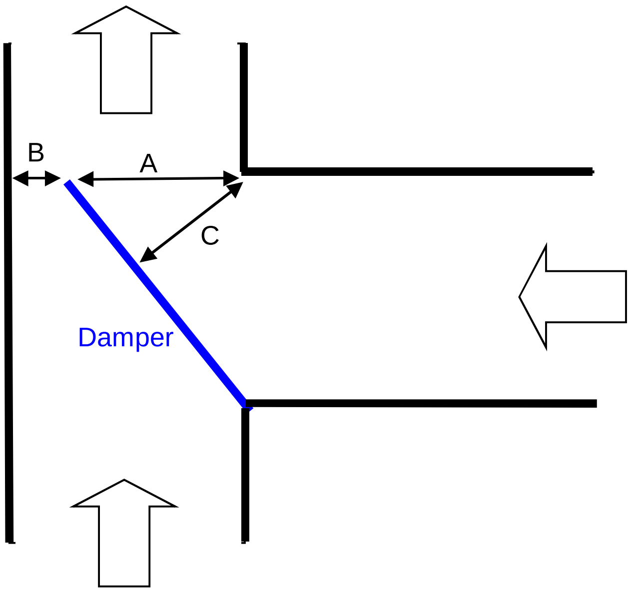


Figure 132 – Cross section of ducts and damper[140]

Flat	Damper opening (A) (mm)	Vertical free area (B) (mm^2)	Horizontal free area (C) (mm^2)	Flow	Notes
95	75	11250	10062	Good	Broken damper, extract fan fitted
81	70	12000	9515	Good	
67	10	21000	1497	Poor	No smoke round grille
53	3-5	21750	750	-	-

Table 20 – Damper opening dimensions

The position of the damper has a twofold effect; it controls the area of the opening between the horizontal and vertical duct and it obstructs the vertical duct. Calculated values of the free area in areas of the vertical (B) and horizontal (C) air paths are also given in Table 20; these assume that the cross section of the duct is approximately 150mm square.

The extract point in Flat 95, directly above Flat 81, had been equipped with a Greenwood Airvac AXS100 extraction fan. This has a maximum flow rate of 2 L/s and is equipped with backdraught shutters. With the fan switched off it would be expected that the shutters would prevent any significant flow from the duct into the bathroom. It is assumed that the fan was controlled by the bathroom light and was not switched on at the time of the fire. This is confirmed by the clean surfaces in the bathroom of Flat 95, although there was some soot around the fan grille.

The damper in Flat 67 was almost closed and there was no visible smoke staining round the grille in the bathroom of Flat 67 indicating that very little smoke entered Flat 67 from the ventilation duct.

There cannot have been any smoke movement through the ventilation duct system from Flat 53 to Flat 81 until after the fire in Flat 53 started at 16:49.

References, such as CIBSE Guide C[151], provide extensive information on the flow characteristics of ductwork and associated calculation methods. While these include provision for ducts with rough surfaces (such as brick work sprayed concrete), details for a lot of the duct network leading to the extract fan in the plant room are not known, so it is not possible to construct a precise representation of the ducts. However, an approximate representation can provide some insight into how the bathroom extraction system contributed to smoke movement in the building during the incident.

The damper arrangement shown in Figure 132 can be represented by a simple network as shown in Figure 133.

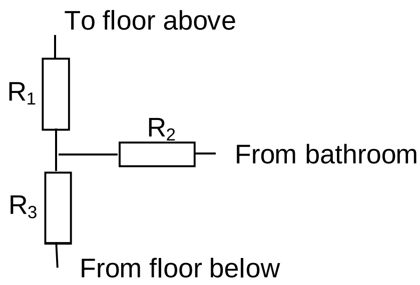


Figure 133 – Duct damper network[140]

Flow resistance R_1 represents the duct leading to the next floor, R_2 the gap C and R_3 represents gap B. The fan in Flat 95 has not been included.

The obstructions caused by the dampers are treated as a simple orifice and the vertical duct between floors treated as a pipe with a rough surface (using the Colebrooke-White equation[151]). The "k" values for these elements are given in Table 21. The flow in the duct assumes that the flow rate in each section of the duct is the same. This is modified later to account for the accumulated flow up the building.

Element	k ($m^3 s^{-1} Pa^{-1/2}$)			
	Flat 53	Flat 67	Flat 81	Flat 95
R_1 (duct)	7.9	7.9	7.9	7.9
R_2 (inlet)	0.01	0.01	0.0009	0.0004
R_3 (main path)	0.014	0.014	0.08	0.08

Table 21 – k values for elements of the elements of the duct damper network

The flow rate in the duct, V (in m^3/s), is found from

$$V = kp^{1/2} \tag{11}$$

Where the pressure difference, p, between Flats 53 and 81 is based on the temperature in each flat. Table 22 gives an estimate of the flow rate for several temperatures.

Temperature difference (°C)	Flow rate (l/s)
100	1.7
500	2.9
1000	3.3

Table 22 – Flow through ventilation duct (extract fan off)

The calculation depends on the square root of the pressure difference between the flats, and the flow rate is not very sensitive to temperature over the range of temperatures (500-1000°C) encountered in a fully developed fire. From the above calculations, the flow induced between Flats 53 and 81 into the duct would have been about 3 L/s. The flow rate is mainly controlled by the small gap at the damper (3-5mm) in Flat 53. This estimate does not include the effect of wind.

The flow rate of 3 L/s would be reduced in practice by buoyant gases travelling directly up the ventilation duct into the rest of the ventilation system; however this would be restricted by the damper at Flat 95 obstructing 50% of the duct area (Table 20). The concentration of fire gases in the bathroom of Flat 81 have been calculated based on flow rates of 3 L/s and 1.5 L/s (50% of the gases going into the ventilation network).

The velocity of the smoke and hot gases in the ventilation duct would have been approximately 0.003/(0.15 x 0.15) = 0.13m/s. For the 10m height difference between the flats, this gives a transit time of ~80 seconds.

Table 23 gives an indication of the CO and CO_2 concentrations in the bathroom of Flat 81, assuming there is complete mixing in the bathroom and using the gas concentrations measured in the reconstruction to represent the fire in Flat 53 (CO ~300ppm, CO_2 ~12%).

Time	Flat 53	Flat 81 bathroom			
		Low flow (1.5 L/s)		High flow (3.0 L/s)	
		CO	CO_2	CO	CO_2
16:49:11	Fire starts	ambient	ambient	ambient	ambient
16:53	CO_2 steps up to 12% (based on reconstruction)	ambient/ near ambient	ambient/ near ambient	ambient/ near ambient	ambient/ near ambient
16:57 smoke observed by Male A		10ppm	0.4%	20ppm	0.8%
17:03		30ppm	1.2%	58ppm	2.3%
17:13		65ppm	2.6%	116ppm	4.6%
17:16	Fire controlled				

Table 23 – Flat 81 CO and CO_2 concentration predictions (plant room fan not running)

Note that at approximately 17:04, the bathroom door was opened. This would allow air from the flat to mix readily with the air in the bathroom reducing the concentrations of CO and CO_2 until the bathroom door was closed.

The concentrations of carbon monoxide are below the limits for 30 minutes exposure for asphyxiant gases given in PD 7974-6[152]; however this exposure would contribute to the total exposure accumulated by the occupants of the bathroom in Flat 81 during the incident.

As the flow rate from Flat 53 into the duct (~3 L/s) is less than the expected design extract rate due to the plant room fan (6.25 L/s), then no smoke should come out of the extract points in the bathrooms under normal conditions.

Paper placed across the grille in Flat 81 was covered with smoke and supports the observation by one of the four in Flat 81 (prior to 17:06) that smoke came in through the grille shortly before he left Flat 81. It can be concluded that either the plant room fan was not running or the position of the dampers and/or accumulated matter in the ventilation ductwork system resulted in the extraction rate in the bathrooms being less than the rate required by the 1972 Building Regulations[150].

If the extract system was running at a very low extraction rate (below 3 L/s), then smoke would move between Flats 53 and 81 and concentrations of gases in the bathroom of Flat 81 would approach the values calculated when the extract system was not running, Table 23.

Statements from two of the four that left Flat 81 describe smoke entering the bathroom of Flat 81 firstly through the ventilation grille and then, after the grille had been covered, from under the bathroom door. This smoke may have come from the corridor through door cracks or gaps round services or from the cracked window and trickle vent in bedroom 1 (see above). These two do not mention smoke in the flat impeding their exit from the flat up the internal stairs, across the living room and out onto the balcony. This indicates that the concentration of smoke in the flat at this time (prior to 17:06) was not very high.

As previously mentioned, prior to 17:06, there were up to nine people (four adults, five children) occupying the bathroom. Considering the small volume of the bathroom it would be expected that the temperature and carbon dioxide concentration would increase quite rapidly without the presence of a fire in the building, especially if there was a low ventilation flow rate.

The presence of the people in the bathroom also decreases the volume of air in the space so that the concentrations of carbon dioxide and carbon monoxide predicted in Table 23 may be underestimates.

3.1.6.10. Smoke in Flat 81 and the Bathroom of Flat 81 after 17:06

After 17:06, smoke in Flat 81 could have originated from:

- The fire on the stairs of Flat 81
- The fire in the corridor through:

- The burning door and door panel
- The fire damaged stairs in Flat 81.

After 17:06, smoke in the bathroom of Flat 81 could have originated from:

- Smoke from Flat 53 (and possibly other flats) via the bathroom ventilation system
- Service openings in the walls and gaps in the structure
    - From the fire in the corridor
    - From the smoke in the remainder of Flat 81

Each of these routes is discussed in the following sections.

Shortly after the four left Flat 81, the fire from Flat 79 entered the 11th floor corridor and rapidly spread. This fire penetrated Flat 81 at the stairs and involved material in the living room near the stairs and the partition between the kitchen and living area. The only supply of oxygen to this fire would have been from the flat as there were no open windows or external doors. The local fire in Flat 81 would have become oxygen starved and did not spread significantly.

Assuming the volume of the flat is approximately 160m^3, then the flat would contain 45kg of oxygen. If 35kg was burnt then the concentration would be reduced to ~5% which would not support further combustion. This quantity of oxygen would support a “Medium” growth fire for approximately 3.5 minutes. During this time a local fire would have reached a peak heat release rate of approximately 500kW.

As the fire in Flat 81 became oxygen limited the concentration of carbon monoxide in the combustion products would have increased, as would vaporised unburnt fuel which condensed as a tarry deposit on the surfaces of the living area in the flat (DSC_6828, Table 15). Therefore within 5 minutes of the fire from the corridor penetrating Flat 81 through the stairs, the atmosphere in the flat would have fallen to a very low concentration of oxygen (~5%) and risen to high concentrations of carbon monoxide and carbon dioxide. These gases could have entered the bathroom of Flat 81 through the door cracks.

Photographs clearly show that at some time during the incident there was burning inside the flat at the top of the door and the top of the door panel (DSC_0104, Table 15). This may have occurred after most of the oxygen in the flat had been consumed by the stair fire as the fire damage over the door is not extensive and there is only a small area of smoke staining on the hall ceiling that could be associated with this with burning near the door. Alternatively this damage could have occurred after (or while) the fire fighters entered the flat; there is support for this from Figure 134 which shows a discontinuity in the smoke damage between the top of the door and the frame. There are no signs of smoke penetration at the front door letterbox or spy hole on Figure 134.

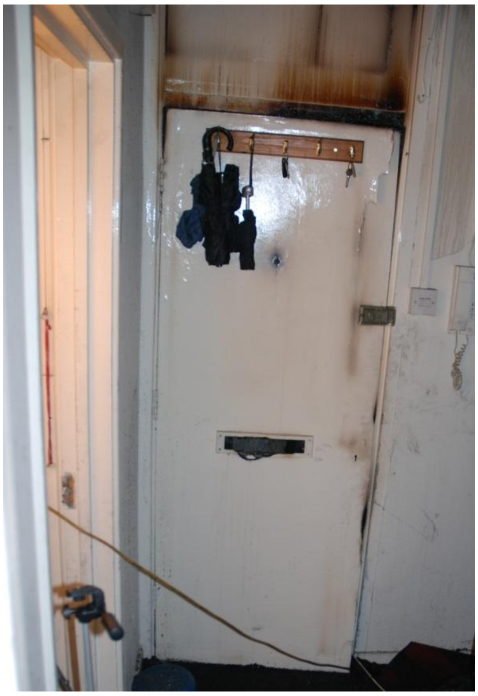


Figure 134 – Front door of Flat 81, showing discontinuity of damage between top of door and frame plus lack of damage around letterbox and spy hole[140]

The internal surfaces of the front door and panel do not appear to have contributed significantly to the smoke inside the Flat 81. Although the door had almost burnt through, there were no signs of a significant flow of smoke at the door edges.

Before the four left Flat 81, two of the nine people are understood to have covered the bathroom ventilation grille with paper from a magazine secured by adhesive (parcel) tape. The paper remained securely fixed until it was removed by fire investigators. The grade of the paper and number of sheets used is not known, but this method of blocking the ventilator grille appears to have been effective in stopping particulate smoke entering the bathroom from the ventilation duct. Photographs show an accumulation of soot on the grill side of the paper but none of the bathroom side (see Figure 135).

Figure 135 – Magazine secured using tape to cover ventilation grille in bathroom of Flat 81[140]

Gases such as carbon dioxide and carbon monoxide could have passed through the paper; however this would have been increasingly restricted by the accumulation of soot on the grille side of the paper.

It appears unlikely that the bathroom ventilation system would have been a significant route for the flow of smoke into the bathroom of Flat 81 after the grille had been blocked by the magazine and adhesive tape.

Due to the number of uncertainties regarding the bathroom ventilation, estimating the rate that the bathroom atmosphere became contaminated from the fire gases in the flat would be very speculative. However, as an indicator, if the ventilation was at the rate required by the Building Regulations 1972[150] and the atmosphere in the flat was as measured during the reconstruction, then the gas concentrations in the bathroom are given in Table 24.

Time (min)	O_2 (%)	CO (ppm)	CO_2 (%)
5	16	66	2.6
10	14	120	4.7
15	12	160	6.3
20	10.5	190	7.6
25	9.3	215	8,5
30	8.3	230	9.3

Table 24 – Flat 81 bathroom predicted gas concentrations

From the discussion of the bathroom ventilation rate above, the actual ventilation rate may have been lower which would reduce the concentrations at each time given in Table 24. However the carbon monoxide concentration for the under ventilated fire in Flat 81 are likely to be much higher than in the reconstruction and consequently, the carbon monoxide values in Table 24 are probably an under estimate.

3.1.7. **Incident Timeline based on Fire Incident Data, Reconstruction and Modelling**

The programme of work undertaken has identified the following to be key points that were significant in the way in which the incident on the 3rd July 2009 occurred. The following details have been compiled from the incident timeline (developed by London Fire Brigade using fire appliance mobilisation reports, entry control logs for breathing apparatus crews, timestamped photographs and witness statements), investigation by BRE, reconstruction data and computer modelling.

From ignition (estimated around 16:15), the fire in Flat 65 developed rapidly on both floors as a result of doors within the flat being left open and windows failing rapidly, ventilating the fire and allowing it to grow until a flashover or backdraught event occurred at approximately 16:25.

The combined fire plumes emitting from the upper and lower floors of Flat 65 (following the flashover/backdraught event) impinged upon the window panels of bedroom 1 of Flat 79. By approximately 16:30, after the window panels had been exposed to flaming from Flat 65 for approximately 4 minutes 30 seconds, a fire had established itself inside of bedroom 1 of Flat 79.

By approximately 16:34, the window panel of bedroom 1 of Flat 79 had burnt away completely, providing ventilation for the fire in Flat 79. This was followed shortly by failure of the glazing of the window set. Note however that, apart from a few short periods when doors were opened and closed, no ventilation paths were generated in the upper floor of Flat 79.

At approximately 16:48, the fire involved the staircase in Flat 79. Less than a minute later, burning debris ignited Flat 37 below. The last sign of breathing from the occupant of Flat 79 was heard around this time. At approximately 16:49, burning debris also ignited Flat 53.

At approximately 16:52, the fire in Flat 79 involved the lobby of Flat 79 and the first flames began to penetrate through the letterbox.

At approximately 16:56, the first peak in fire growth occurred in Flat 37 and at 16:59 the first peak in fire growth occurred in Flat 53. The first reports of smoke entering the bathroom of Flat 81 (connected to Flat 53 via the bathroom extraction system) were at approximately 16:57.

At approximately 16:59, the fire in Flat 65 was subdued as a result of intervention by London Fire Brigade. At approximately 17:00, the decision was made by London Fire Brigade to move the bridgehead out of the building (as a result of smoke logging throughout the remainder of the building).

At approximately 17:06, four individuals left the bathroom of Flat 81 and proceeded to the East side balcony of Lakanal House. At this stage the four individuals evidently considered the route through Flat 81 to be tenable.

At approximately 17:08, the fire in Flat 79 breached both the panel above the front door and the boxing in under the timber stairs. Given how close their failure times were in the reconstruction fire, it is not possible to confidently state which of these elements would have failed first during the incident.

At approximately 17:16, the fire in Flat 53 was subdued by London Fire Brigade.

At approximately 17:20, the front door of Flat 79 collapsed into the 11th floor corridor, allowing a severe fire to spread down the corridor. This is supported by a photograph showing smoke emitting from the end of the communal corridor at 17:22:15. Smoke from the corridor fire would be beginning to enter the bathroom of Flat 81 through gaps in wall construction.

From approximately 17:30 to 17:35, the boxing in beneath the stairs in Flat 81 would, given its performance in the reconstruction fire, be expected to have been reaching the limits of its fire resistance capacity. Fire and large quantities of smoke would have begun to enter the remainder of Flat 81.

At approximately 17:36 London Fire Brigade fire fighting crews encountered a severe fire in the 11th floor corridor. They encountered significant difficulty in progressing along the corridor due to a number of factors:

- The complex layout of Lakanal and presence of front doors and escape doors for each of the flats (see section 3.1 and Figure 49).
- The severity of the fire in the 11th floor corridor having burnt flat numbers off of doors.
- The severity of conditions in the 11th floor corridor (in particular the hot concrete structure) causing fuel items to spontaneously reignite after they had been extinguished by fire fighting.
- Fire fighters rapidly running out of air once they had ascended 11 storeys of staircase to fire fight (N.B. the fire fighting lift was not functioning during the incident). LFB switched to Extended Duration Breathing Apparatus to mitigate this, but then fire fighters began suffering heat exhaustion and physical exhaustion.

At approximately 17:42 the fire in Flat 37 was extinguished by London Fire Brigade.

At 17:44 the last call was answered by occupants of the bathroom of Flat 81.

At approximately 18:20 to 18:30 London Fire Brigade entered the bathroom of Flat 81. Three casualties were found and removed. Fire fighting continued throughout the building until three further casualties were found in Flat 79 and the bathroom of Flat 81.

3.1.8. **Sequence of Events Relevant to Analysis**

3.1.8.1. Flat 79

Fire development within Flat 79 was investigated by the completion of the full-scale reconstruction and relevant computer modelling. The fire in Flat 79 started as a result of fire from Flat 65 igniting the outer surface of the composite panels in the bedroom window sets. These panels burnt through and ignited the contents of Flat 79 (most probably the curtains).

Fire development within Flat 79 does not appear to have produced a flashover as is normally expected in compartment fires. The fire initially involved the fuel load nearest the window façade, producing an initial peak in heat release rate, then gradually progressed into the flat towards the internal flat staircase, where a second peak in heat release rate and associated temperatures occurred.

The data used to complete the FED analysis for the upper floor of Flat 79 is shown in Figure 136. Given that the fatality occurred outside of the space represented by the reconstruction rig, the computer modelling has to be relied upon to some extent to establish the relevant conditions, although more data is available from the reconstruction fire. Comparing the temperature prediction from JASMINE (Figure 119) with the closest temperature data from the reconstruction (thermocouple at 2.8m above ground on Figure 77) shows reasonable agreement between them. However the only data that is available for toxic gas species is that from the reconstruction.

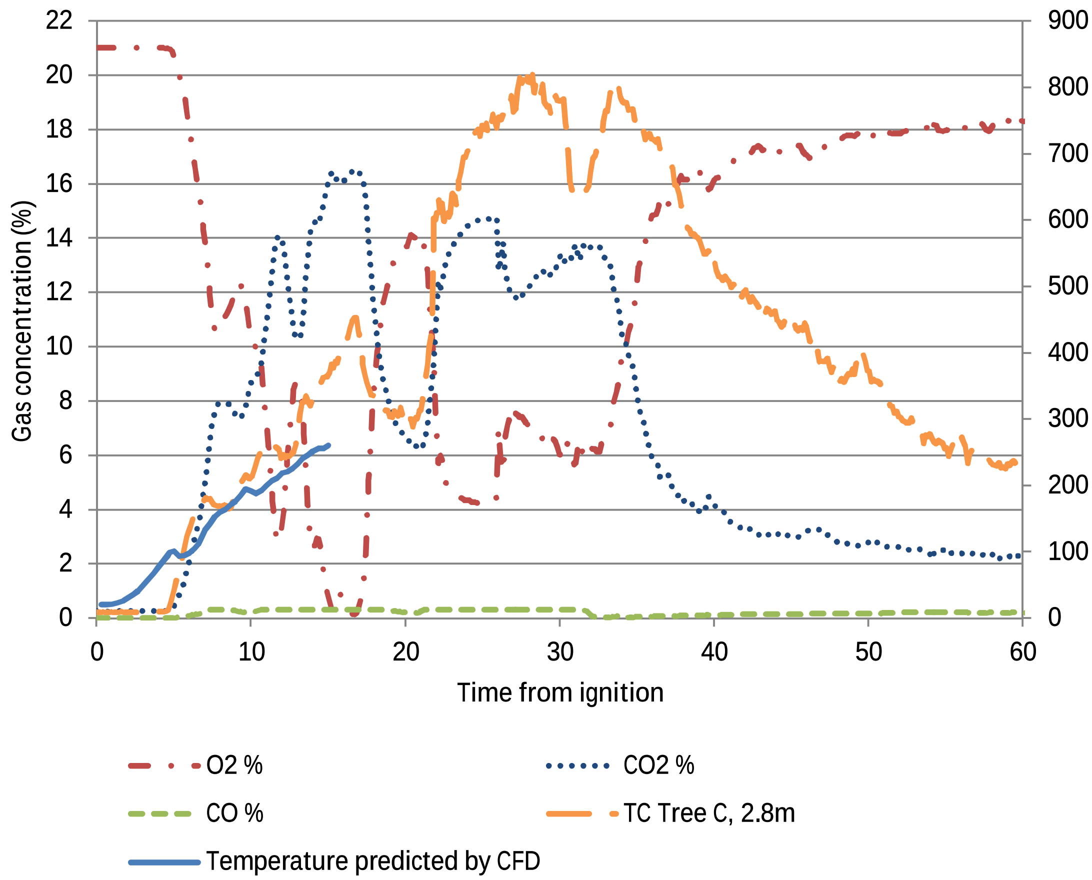


Figure 136 – Data used from Lakanal reconstruction data headspace measurements for FED calculations

3.1.8.2. Bathroom of Flat 81

The various ways in which the fire affected the conditions in Flat 81 have been covered in sections 3.1.6.8 to 3.1.6.10, so will not be repeated here. A number of leakage paths and areas of burning in Flat 81 (notably the staircase) all contributed to toxicity of the atmosphere throughout the flat. In addition, the bathroom extraction system is known to have contributed to the toxicity of the atmosphere in the bathroom of Flat 81 before attempts were made to block it up. The values given in Table 25 are based on consideration of those events, then also assume some extraction would have resumed from Flat 81 once the fire in Flat 53 (overwhelming the extraction system) was extinguished. Assuming linear changes in gas concentrations produces the data shown in Figure 137.

Time during incident	O_2 (%)	CO (ppm)	CO_2 (%)
17:25	16	66	2.6
17:30	14	120	4.7
17:35	12	160	6.3
17:40	10.5	190	7.6
17:45	9.3	215	8,5
17:50	8.3	230	9.3

Table 25 – Flat 81 bathroom predicted gas concentrations

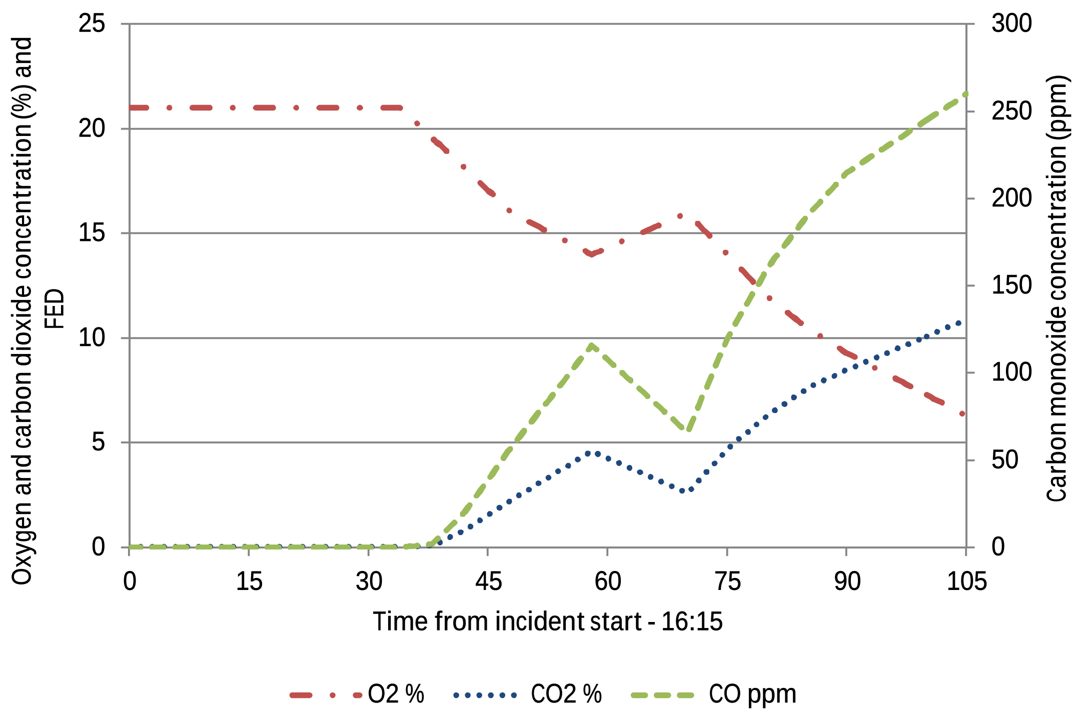


Figure 137 – Data used from Lakanal Flat 81 gas concentration calculations for FED calculations

3.1.9. **FED Data from Experimental Data**

The hazard analysis for Flat 79 confirms the discussion in section 3.1.4.5 regarding conditions appearing more severe than was actually the case due to the restricted headspace. The victim in this area survived until a time corresponding with 24 minutes from ignition and is known to have died from a combination of burns and smoke inhalation. It is known that she was sheltering on the floor near a door to the outside and so it is likely that fresh air was entering the area through this point. This would have diluted the fire gases and had some effect on the temperatures in the space.

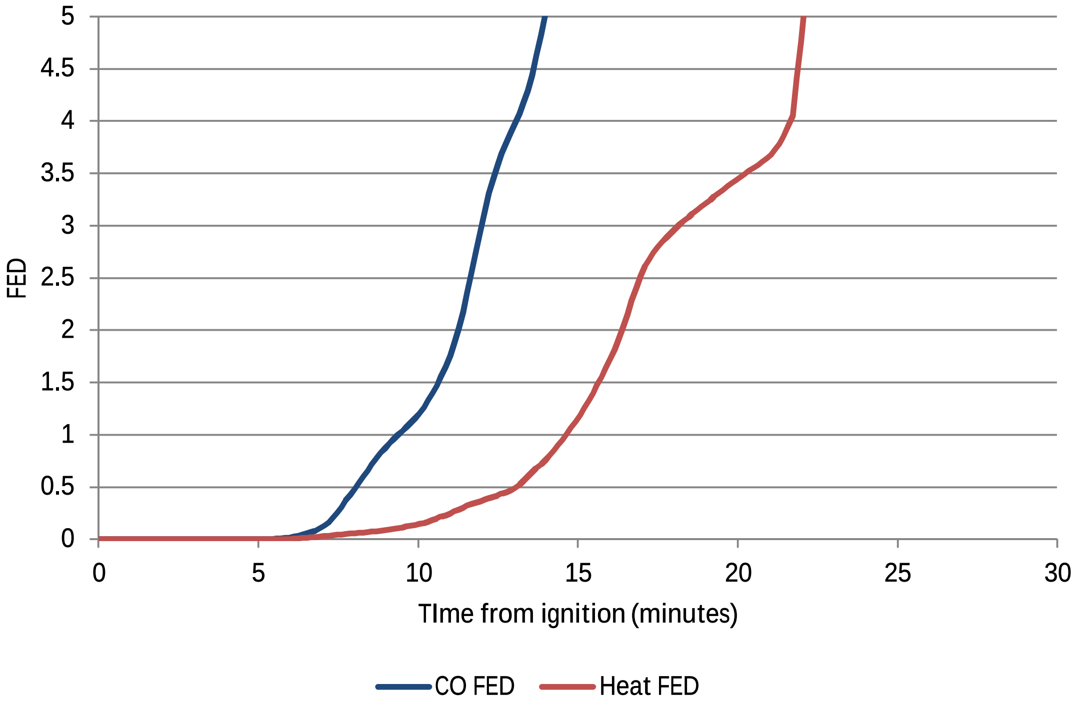


Figure 138 – FED values calculated using ISO 13571 method based upon Lakanal reconstruction data relevant to the fatality in Flat 79

The gas concentrations used for the hazard analysis of the bathroom of Flat 81 necessarily the idealised outcomes of several steps of computer modelling and engineering analysis to bring together all of the contributing factors in the Lakanal fire. It is interesting to note that, albeit without any consideration of other toxicants, the time at which FED exceeds 1, just before 105 minutes, coincides with the likely time of death for the victims that was reported at the inquest (18:00).

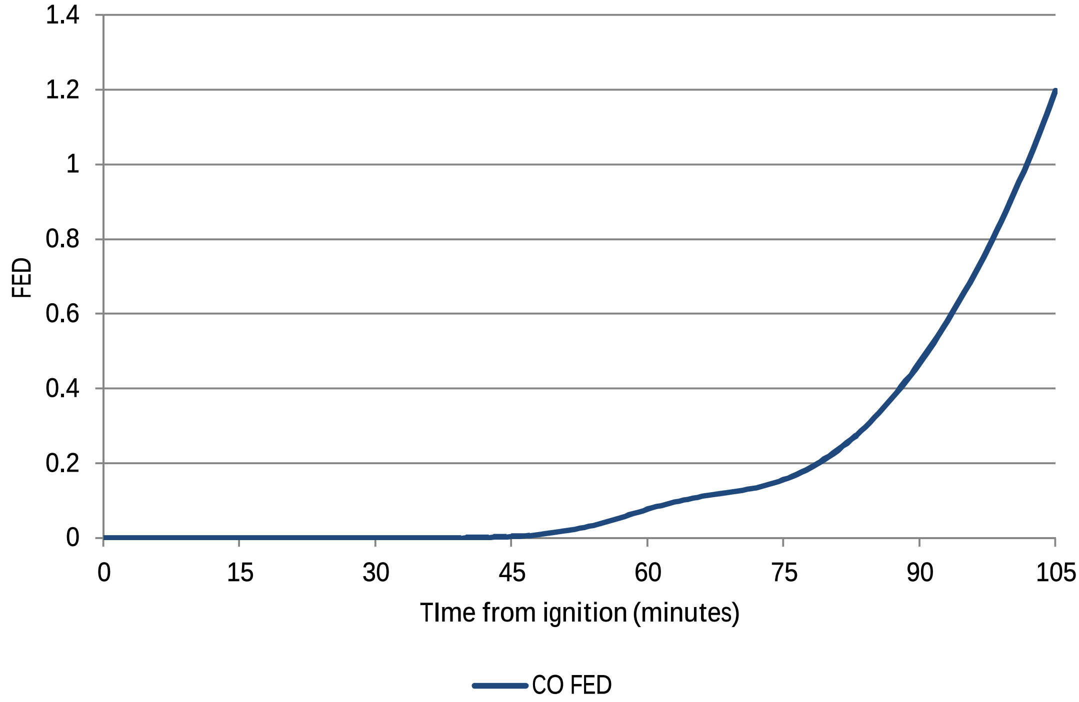


Figure 139 – FED values calculated using ISO 13571 method based upon reconstruction, modelling data and engineering calculations for the bathroom of Flat 81

3.2. Atherstone-on-Stour

On 2nd November 2007, a fire broke out in the vegetable packing warehouse of Wealmoor Atherstone Limited, Hanger [sic] 1 and 2 in Atherstone-on-Stour, Warwickshire (the premises are hereafter referred to as Wealmoor Atherstone). The fire ultimately resulted in the collapse and total loss of the building and claimed the lives of four fire fighters. One of the principal concerns with regards to the lives that were lost was the means by which the fire suddenly developed and spread throughout the building during the incident. Of particular interest was the period leading up to the incapacitation and deaths of the four fire fighters (i.e. during the period from some time after 17:00, when ignition is understood to be likely to have occurred, to 19:30).

Wealmoor Atherstone was a vegetable packing warehouse measuring approximately 150 metres long by 69 metres wide and 10 metres high, see Figure 140. The building was of steel frame construction, with various parts of the building clad in either steel sheet or insulated sandwich panels.

The building is understood to have undergone a number of extensions and refurbishments since its original construction as a World War II aircraft hangar (the specific year of construction is not known). The most recent refurbishment and extension is understood to have started in 2005. This work included refurbishment of the existing building and extending the premises with the addition of another large steel framed building. A number of fire safety features are understood to have been included in designs for this extension and refurbishment due to requirements made by the insurer for the property.

The company owning Wealmoor Atherstone (then Bomfords Limited) went into insolvency and entered administration in June 2007, while the refurbishment and extension work was still on-going. Construction work ceased at the time of entering into administration, resulting in a number of the fire safety features of Wealmoor Atherstone not being completed. A smoke detection system is understood to have been partially installed but not completed. A suppression system is understood to have been designed but had not been fitted at the time of the fire. The building is understood to have then been bought by Wealmoor Atherstone Limited in August 2007.

The building was divided into three sections by two four-hour fire-resisting walls. These three sections can be seen on Figure 140 as sections A, B and C.

Section A was the east end of the building. This Section comprised two storeys with refrigerated stores and a goods out area on the ground floor and predominantly offices and staff facilities on the first floor. The main route used by WFRS (Warwickshire Fire and Rescue Service) personnel to access the fire was through the first floor of Section A.

Section B was the central part of the building. This Section also comprised two storeys; a ‘pack house’ (used for packaging produce) on the ground floor and a large storage area on the first floor. It is understood that the fire started in the upper floor of this Section and that WFRS personnel were in the upper floor of this Section when a sudden fire development event occurred which resulted in a BA emergency and ultimately the deaths of the four fire fighters.

Section C was the west end of the building. This section was single storey and comprised the original aircraft hangar and the first extension that had been added. Events that occurred in this Section with respect to the incident are not directly relevant to the objectives of this programme of work so they are not considered further.

Given the scale of the incident, as there is no fire laboratory (nor is one likely to ever be constructed) that is capable of containing a building of Wealmoor Atherstone's size, a combined approach of reconstruction and computer modelling was carried out. The reconstruction was used to physically replicate the conditions around the area of fire origin and the development of the fire in this area, whilst computer modelling would allow data from the reconstruction to be applied to the building in its entirety.

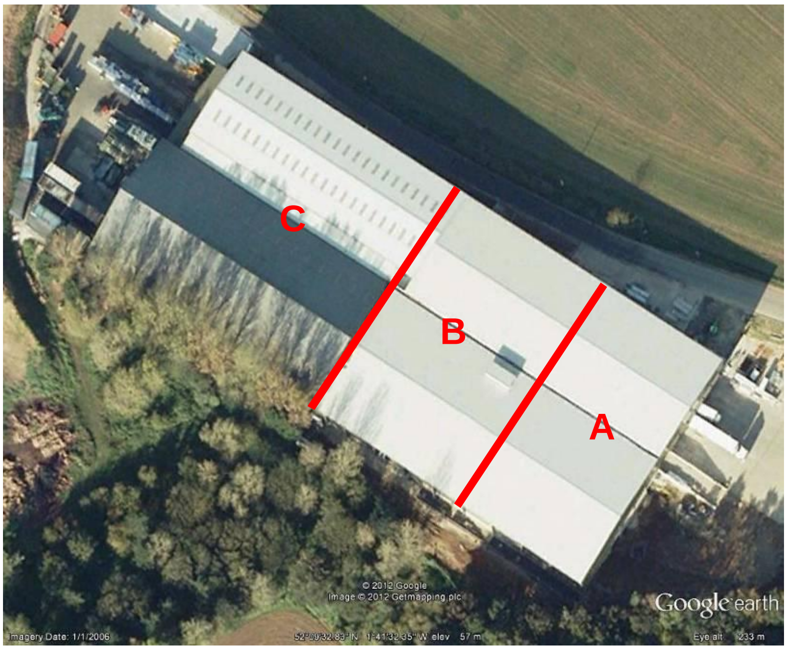


Figure 140 – Aerial view of Wealmoor Atherstone prior to fire showing three sections identified by Hereford and Worcester Fire and Rescue Service fire investigation. The fire started in the first floor of Section B. Image from Google Earth, dated December 2006 (© 2012 Getmapping Plc, © 2012 Google)

The building is understood to have undergone a number of extensions and refurbishments since its original construction and included a number of fire safety features. Some of these were complete whilst others were incomplete. Further details of this can be found in the BRE report into the fire reconstruction and modelling[153].

3.2.1. **Reconstruction Setup**

It was only possible to re-create a relatively small partial representation of Wealmoor Atherstone in the Burn Hall. This was intended to provide a representation of the way in which fire would develop and spread within an environment representative of the environment in Wealmoor Atherstone, but with the knowledge that data obtained from the reconstruction would have to be adapted using computer modelling to be made applicable to the incident as it occurred.

The reconstruction rig was designed to be a partial representation of one of the bays in the first floor of Wealmoor Atherstone; the bay in which the fire is understood to have started. This partial reconstruction was to represent the vertical space and relevant structures between the upper surface of the suspended ceiling on the ground floor and the top of the building, as shown in Figure 141. The layout of the reconstruction rig is shown later in Figure 147.

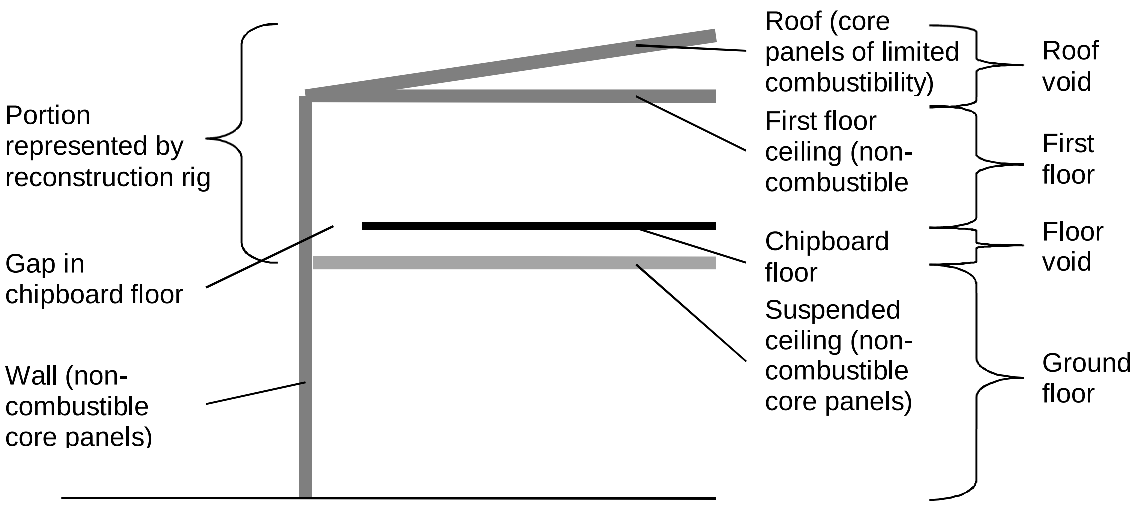


Figure 141 – Portion of Wealmoor Atherstone elevation Section B that it represented by reconstruction rig

The incorporation of representations of the various features shown in Figure 141 was intended to allow analysis of the effect of these features on a developing fire so that this could be accurately included in the computer modelling.

The layout and construction of the reconstruction rig is shown in Figure 142 to Figure 144. At one end of the rig, a room was built with a design and method of construction that was intended to be representative of the construction of Wealmoor Atherstone.

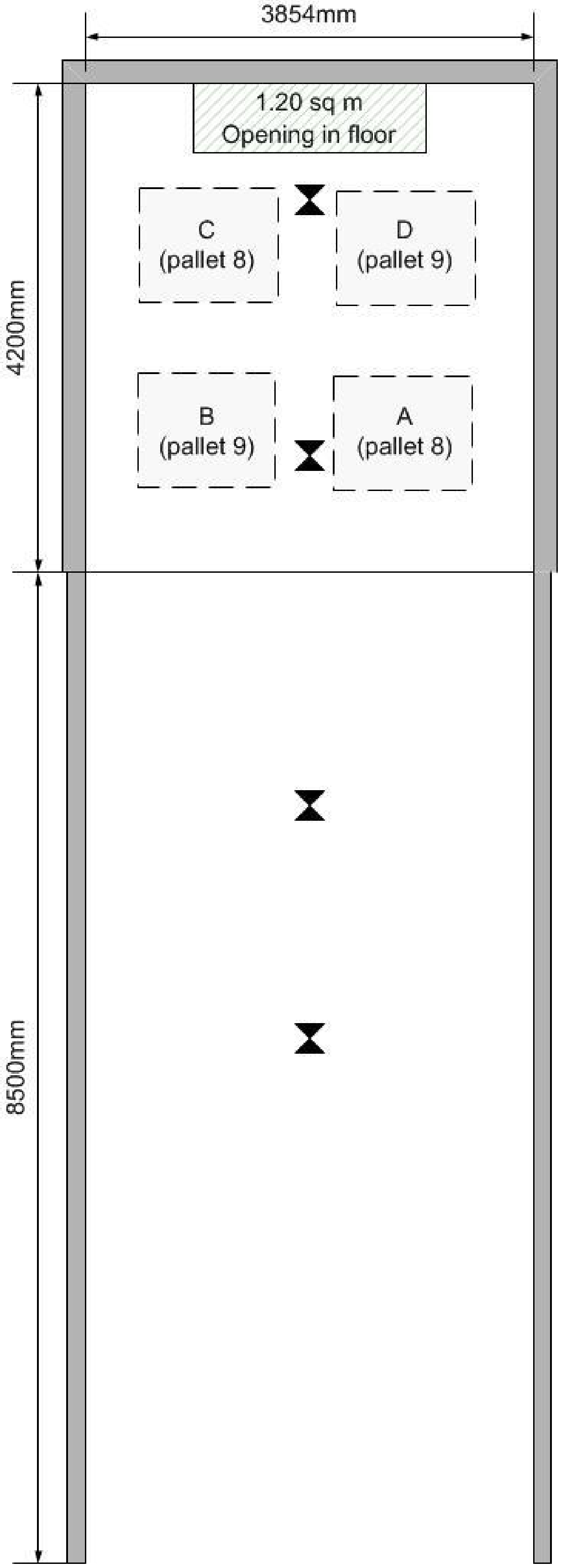


Figure 142 – Layout of Atherstone reconstruction rig, showing the positions of the four pallets in each reconstruction and the opening to the rear of the rig

Figure 143 – External view of steel frame and sandwich panel room prior to reconstruction

Figure 144 – External view of timber frame and plasterboard corridor prior to reconstruction

The insulated panel walls, ceiling and roof were intended to provide a level of insulation that was representative of the level of insulation in Wealmoor Atherstone. This would ensure that the containment of heat in the reconstruction rig would be representative of the containment of heat that occurred in Wealmoor Atherstone during the incident, so that the impact of this containment of heat on the burning conditions and development of the fire could be assessed.

A suspended floor was included in the reconstruction rig. The floor was intended to represent the chipboard floor of the first floor of Wealmoor Atherstone, which covered a significant area;

approximately 5500m^2 across sections A and B. Suspending the floor above the laboratory floor allowed assessment of the effect of ventilation to the rear of the room through the floor void. It is understood that there were openings in the chipboard floor against the external wall of Wealmoor Atherstone in the area where the fire started. These openings had been left to allow access into the void between the chipboard floor and the suspended ceiling above the ground floor. However, this provided a ventilation route along the void and up through the opening in the floor into the rear of the bay where the fire started.

Extending out from the room was a corridor. The internal cross-sectional area of the corridor was the same internal cross-sectional area as the room; including the suspended floor and floor void (i.e. the wall and ceiling surfaces of the corridor were flush with those of the room). The corridor was intended to provide a non-combustible channel, representative of some of the remainder of the bay of Wealmoor Atherstone. This would mean that the ventilation available to the fire would be representative of that present in Wealmoor Atherstone, both for entrainment of fresh air and movement of fire gases. The open end of the corridor was situated below the 9m calorimeter so that the fire gases (O_2, CO,CO_2) leaving the open end of the corridor would be collected for calorimetric analysis.

As it is not possible to fully and exactly re-create the conditions under which an incident as complex as a fire has occurred, there were some differences in the experimental design and testing. It was not possible to reproduce the ambient conditions around Wealmoor Atherstone on 2nd November 2007 for the reconstruction. In particular, at the date of the reconstruction fires) the temperature was lower (~10°C) compared to the day when the fire occurred at Wealmoor Atherstone (~10°C to 17°C). Given the severity of the fire, these differences in ambient conditions (also pressure, humidity, etc.) are not considered to have been significant.

It was also not possible to fully re-create the wind conditions around Wealmoor Atherstone. The area of fire origin was some way within Wealmoor Atherstone so is unlikely to have been directly affected by the wind. However the building may have become pressurised as a result of a door facing upwind being opened. It was assumed that any differences in local air velocities or wind-induced pressure changes would not impact significantly upon the development and spread of the reconstruction fire.

The reconstruction rig could not be constructed using exactly the same materials that comprised Wealmoor Atherstone and the nearest substitutes were used that would be appropriate for the reconstruction rig. It was assumed that differences in these construction materials would not impact significantly on the reconstruction fire.

It was not known exactly what was present on the pallets that are understood to have been in the area of fire origin in Wealmoor Atherstone. WFRS sourced these contents for the reconstruction fires based upon information provided by Warwickshire Police for the Warwickshire Police reconstruction that was carried out at BRE. It was initially assumed that any difference in these contents would not impact significantly on the reconstruction fire. However, the findings of the first reconstruction indicated that the contents of the pallets did have a significant impact.

The actual sequence of pallet ignition in the fire incident is not known, although it is understood that the initial pallet involved in the fire had been identified by a witness (pallet 8).

3.2.1.1. Fuel Load

The contents of the room for the reconstruction fires were provided by WFRS. In each reconstruction there were four pallets of materials. For Reconstruction 1, the materials on all four of the pallets comprised boxes of labels that represented two pallets, identified as Pallets 8 and 9 in the Atherstone bay. The layouts of pallets 8 and 9 are shown in Figure 145.

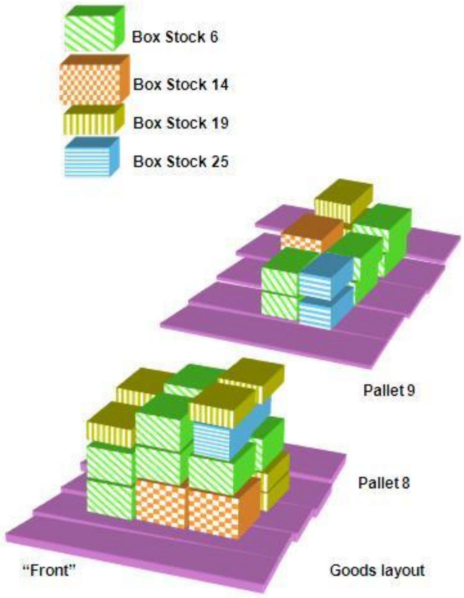


Figure 145 – Layout of boxes on pallets 8 and 9 from the Warwickshire Police reconstruction

For Reconstruction 2, in addition to the boxes of labels detailed above which were present on two of the pallets, WFRS sourced plastic materials to be stacked onto the other two pallets. The layouts of the two pallets of plastic packaging materials can be seen in Figure 146.

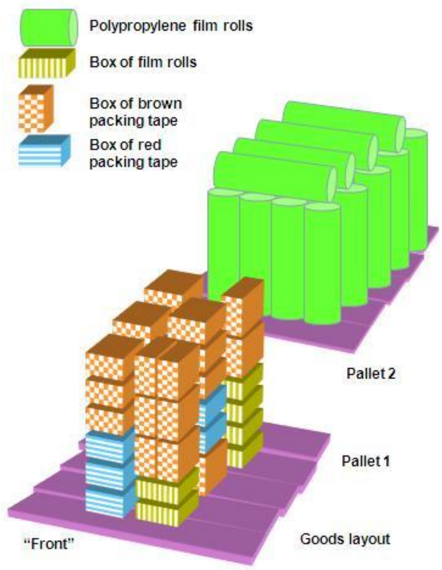


Figure 146 – Layout of boxes on pallets of materials sourced by WFRS

3.2.1.2. Instrumentation

Columns of thermocouples (thermocouple trees) were installed at key locations in the rig. All of the thermocouple trees were installed along the centre line of the rig (i.e. halfway between the left and right walls). Thermocouple tree A was installed 1m from the rear wall of the room and thermocouple tree B 1m into the room from the front edge of the chipboard floor, both along the centre line of the room. Thermocouple tree C was installed in the corridor 2m from the front edge of the chipboard floor and thermocouple tree D was installed in the corridor 4m from the front edge of the chipboard floor.

Thermocouple trees A and B each had 10 thermocouples spaced at 350mm intervals measured from the ceiling, except the lowermost thermocouple which was placed against the floor. Thermocouple trees C and D each had 10 thermocouples spaced at 400mm intervals measured from the ceiling, except the lowermost thermocouple, which was placed against the floor.

The surface of the chipboard floor was instrumented using four thermocouples. The temperatures of the lower and upper surfaces of the chipboard floor were measured, each surface with two thermocouples situated halfway between the front and rear of the room, of which each thermocouple was 1m from either the left or right hand wall.

The void between the ceiling and the roof was instrumented using four thermocouples. Air temperatures were measured by thermocouples installed halfway between the front and rear of the room, 50mm above the ceiling panels and 50mm below the roof panels, all 1m from either the left or right hand wall.

Heat flux meters were installed in two locations in the reconstruction rig. A heat flux meter was installed at the base of thermocouple tree C and another at the base of thermocouple tree D, both orientated upwards so that they would measure downward heat flux from the hot smoke layer in the corridor.

The locations of the instrumentation in the reconstruction rig are shown in Figure 147. Data from all of the instrumentation were logged electronically using the Burn Hall logging systems. WFRS provided a pump and crew for both reconstruction fires.

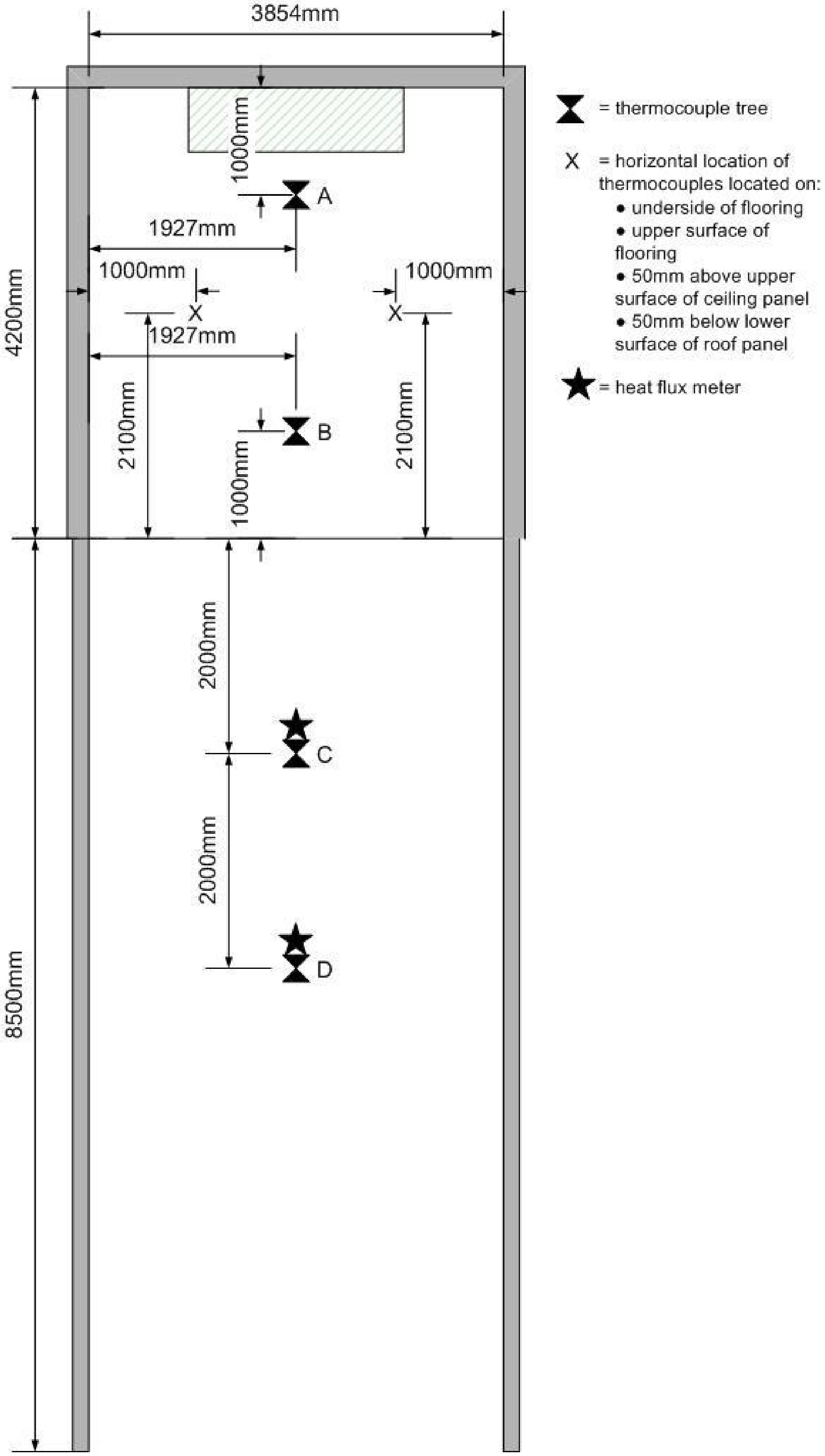


Figure 147 – Plan view of reconstruction rig showing the instrumentation locations

3.2.2. **Reconstruction Results**

Reconstruction 1 produced a fire which was relatively steady fire for three and a half hours before it was extinguished. Given that the reconstruction had been carried out to investigate conditions that might be capable of causing the deaths of fire fighters, a second reconstruction was commissioned in conjunction with further investigative work concerning the materials present in Wealmoor Atherstone (detailed above). Reconstruction 2 produced a fire that remained relatively steady for one hour and then underwent significant development, ultimately requiring extinguishment for reasons of safety.

3.2.2.1. Reconstruction 1 and Results

Observations compiled from the first fire recreation scenario video footage are presented in Table 26.

Time from ignition (hours: minutes: seconds)	Notes
00:00:00	Apply flame to back of pallet A to start ignition
00:00:24	Flame removed
00:01:53	Flame reapplied
00:02:22	Flame removed
00:03:19	Flame reapplied
00:03:51	Flame applied to new location on lower box on pallet A
00:04:06	Flame removed
00:05:23	Flame applied along length of lower box on pallet A
00:05:50	Flame removed
00:06:09	Top box on pallet A opens up
00:06:47	Top right back box on pallet A ignites
00:07:00	Fire dies back
00:08:31	Fire becomes established toward centre
00:11:50	Fire has spread over top surfaces of pallet A
00:12:18	All top surface of pallet A involved in fire
00:13:13	Flames from left hand side of pallet A
00:13:23	Collapse into centre from pallet A
00:17:33	Front left of pallet A falls forwards ('debris' in aisle temporarily alight)
00:45:31	Right hand stack of boxes begin to fall into centre of pallet A
00:45:51	Right hand boxes have fallen into pallet
00:46:17	Fire under pallet A
00:46:56	Dark smoke
00:47:00	Flames visible under pallet A
00:47:30	Flames from under pallet A reach right
00:48:00	Flames from under pallet A reach forwards
00:48:18	Flames from under pallet A on 3 sides
00:50:06	Flaming in centre (debris on floor)
00:55:30	Collapse of front of pallet A forwards
00:55:53	Smoke from under-floor at back right of rig
00:56:56	Flames on debris in centre aisle reach pallet B
01:09:33	Pallet A rounded heap with flames over surface, especially in centre, smoky
01:11:31	Fire builds up at back of pallet A
01:13:15	Pallet D ignited
01:16:12	Pallet D top surface burning

Time from ignition (hours: minutes: seconds)	Notes
01:25:47	Rolls of labels fall into aisle
01:29:04	Collapse of pallet D
01:41:38	Flames on pallet D grow in height
01:43:06	Flames on left hand side of pallet D
01:43:14	Flames under pallet D fanning backwards
01:44:51	Floor at back of rig alight
01:44:56	Collapse at back of rig, visible smoke
01:46:01	Surface on back wall deformed
01:48:49	Pallet C box surface 'browning'
01:50:14	All top surface pallet D involved in fire
01:54:15	Flames at base of pallet B
01:56:27	Collapse backwards pallet D
01:56:50	Pallet D slumps inwards - charred boxes visible on pallet C
01:57:56	Pallet C ignites in corner
01:58:44	Pallet D smoking
02:00:56	Boxes on corner of pallet C charred away (reflections from contents)
02:11:31	Glowing drops start falling periodically from under-floor on right hand side
02:12:28	Collapse at back of pallet D, backwards
02:16:51	Glowing drops start falling periodically from under floor towards the back
02:28:14	Right hand side under-floor glowing
03:29:47	Water on

Table 26 – Significant observations from video footage of Reconstruction 1

The temperature data obtained from thermocouple trees A and B are given in Figure 148 and Figure 149. The temperature data obtained from thermocouple trees C and D are given in Figure 150 and Figure 151.

The data from thermocouple tree A show temperatures remaining relatively stable throughout the reconstruction. There are a couple of spikes in the temperature measurements at locations low down on the thermocouple tree. These appear to have been the result of burning material falling off the pallets and landing in close proximity of the thermocouple tree, allowing flames to impinge directly on the thermocouples. Temperatures for thermocouple tree B show further evidence of the effect of burning material falling in close proximity of the thermocouple tree, with erratic temperature measurements at thermocouples located low down on the thermocouple tree. Temperature measurements at higher level are consistent with the temperatures measured at higher level on thermocouple tree A.

Thermocouple trees C and D measured temperatures that were consistent with the temperatures measured at high level on thermocouple trees A and B. As with thermocouples trees A and B, peaks and troughs in the data recorded from thermocouple trees C and D correspond well with events that caused a flare up in the burning of the materials or exposure of hot embers.

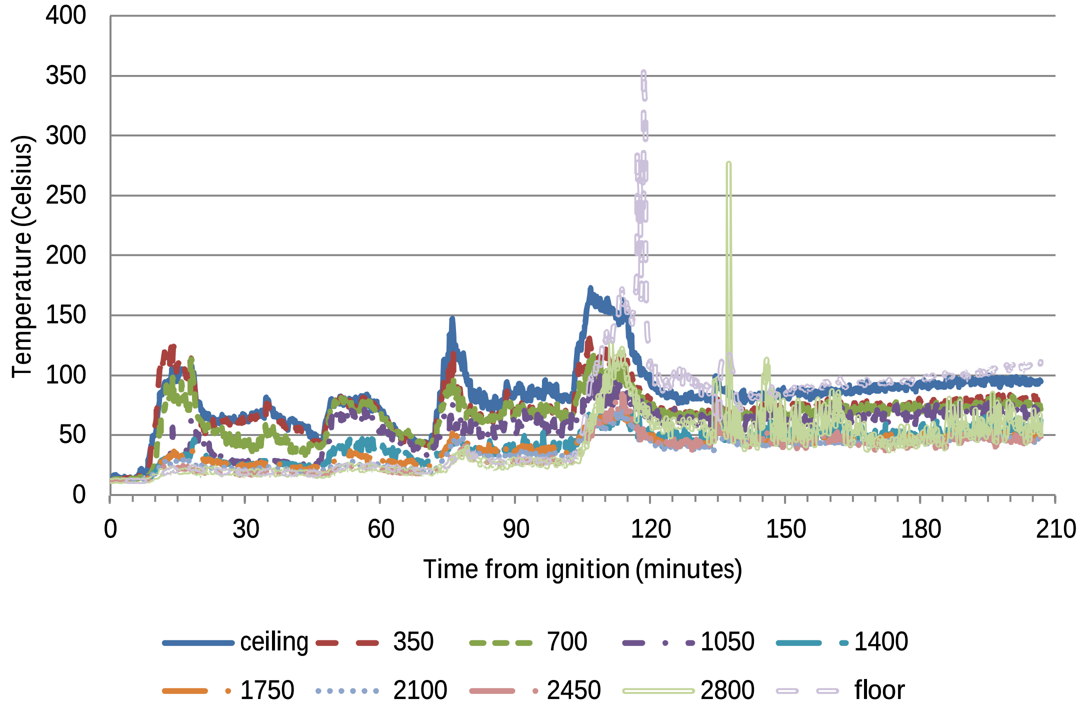


Figure 148 – Temperature data at thermocouple tree A during Reconstruction 1

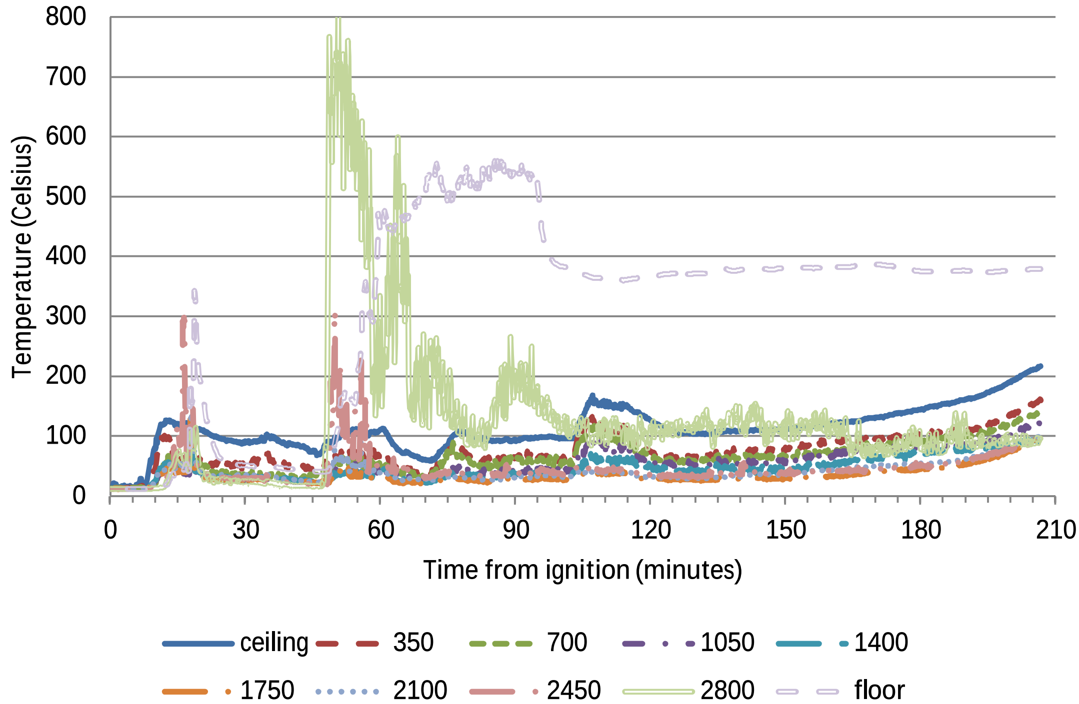


Figure 149 – Temperature data at thermocouple tree B during Reconstruction 1

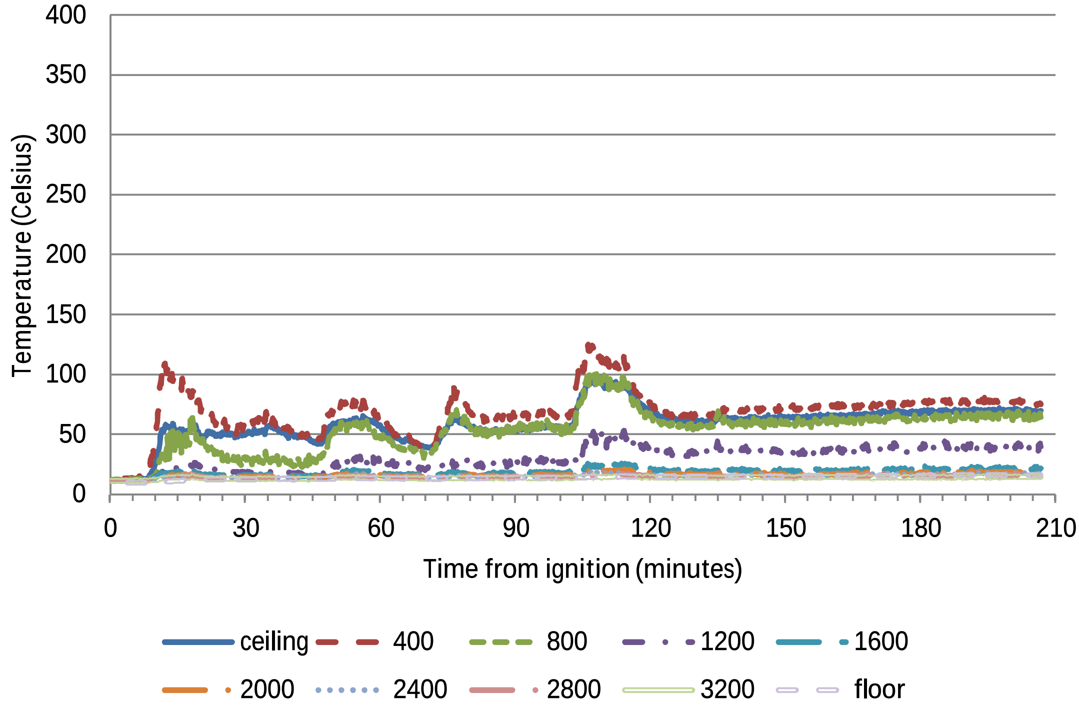


Figure 150 – Temperature data at thermocouple tree C during Reconstruction 1

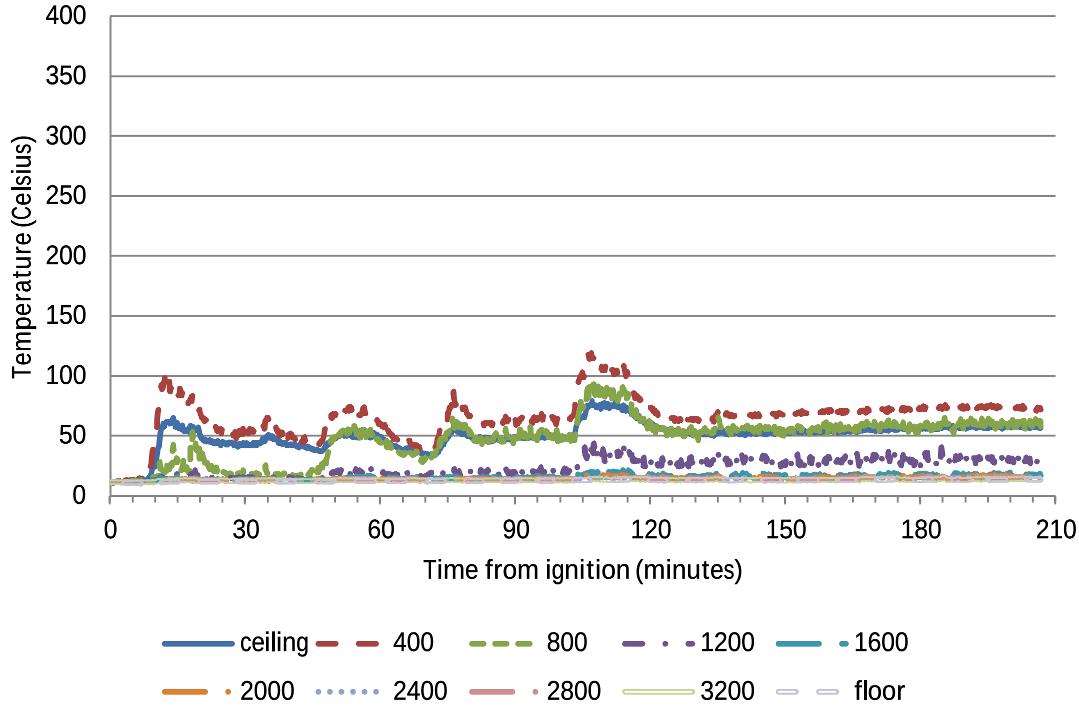


Figure 151 – Temperature data at thermocouple tree D during Reconstruction 1

The thermocouples installed in the ceiling void, Figure 152, show a gradual increase in temperature throughout the reconstruction. There is a marked increase in the rate of temperature rise occurring only during the period when pallet D becomes well involved in the fire. This period coincides with the period when the heat release rate of the reconstruction fire is at its greatest, shown in Figure 155.

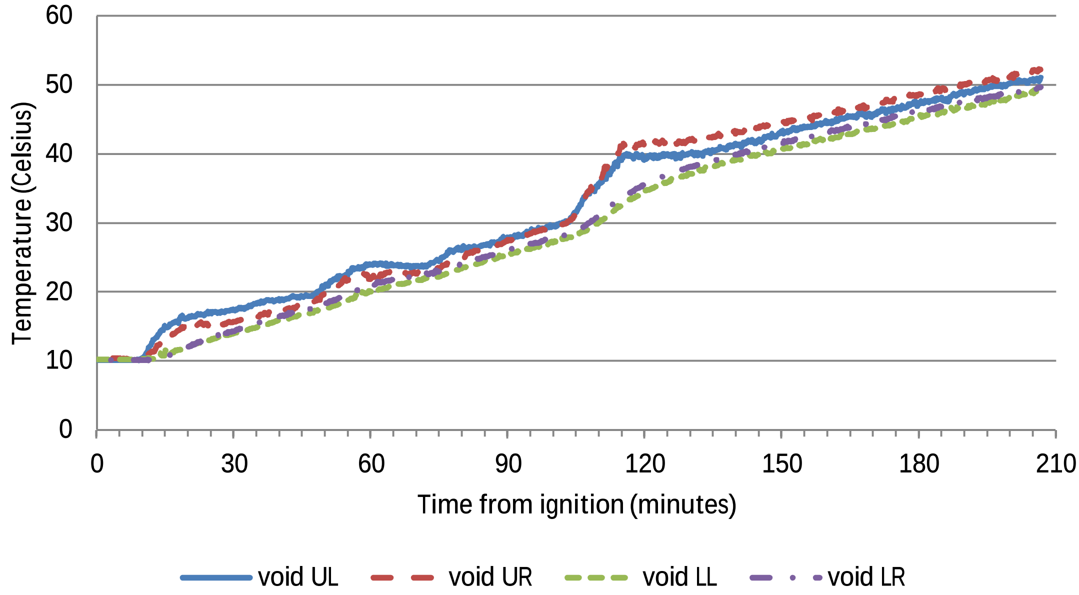


Figure 152 – Temperature data at thermocouples located in ceiling void during Reconstruction 1

The thermocouples installed on the upper and lower surfaces of the floor show temperature increases that are dominated by the spread of fire through the fuel bed on top of the floor. The data collected from these thermocouples can be seen in Figure 153.

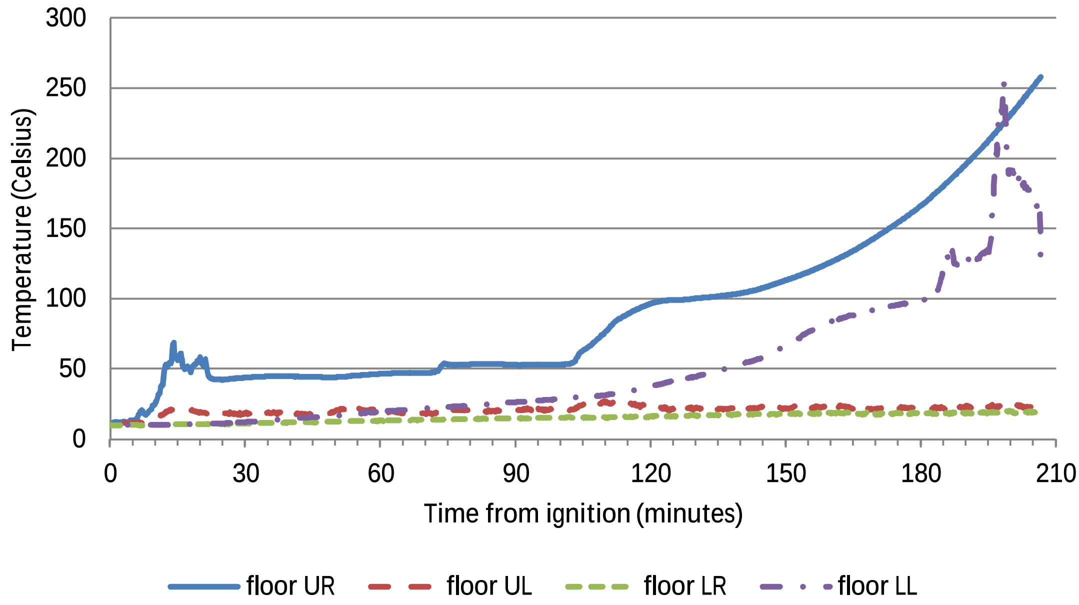


Figure 153 – Temperature data at thermocouples located on upper and lower surfaces of suspended floor during Reconstruction 1

The measured heat flux meter data are presented in Figure 154. The data show a relatively steady increase in heat flux as the fire has developed. The marked difference between the 2m (near) and 4m (far) heat flux meters appears likely to be due to the 2m heat flux meter 'seeing' the flames from the fire (i.e. the flames from the fire were within the viewing aspect of the heat flux meter). The 4m heat flux meter only received heat flux from the hot smoke layer, which was minimal as the smoke layer temperature in the corridor did not exceed 200°C.

The calorimetry data collected from Reconstruction 1 reflect the findings detailed so far. The peaks on the data are accounted for by the preceding involvement of significant elements of the contents of the reconstruction. Significant events considered likely to account for these peaks are marked on Figure 155.

Over the duration of the reconstruction fire, the 9m calorimeter, measuring heat release from smoke exiting the corridor of the rig, registered one main peak of 1.56 MW.

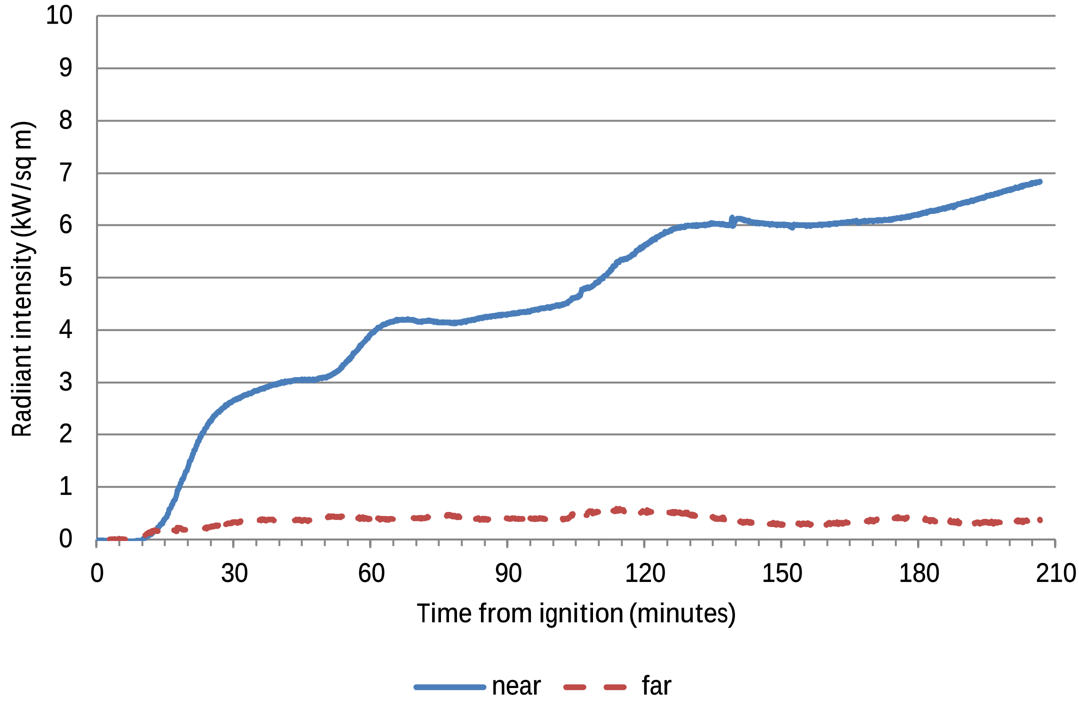


Figure 154 – Radiant heat fluxes measured at floor level inside the corridor 2m (near) and 4m (far) away from the front edge of the room during Reconstruction 1

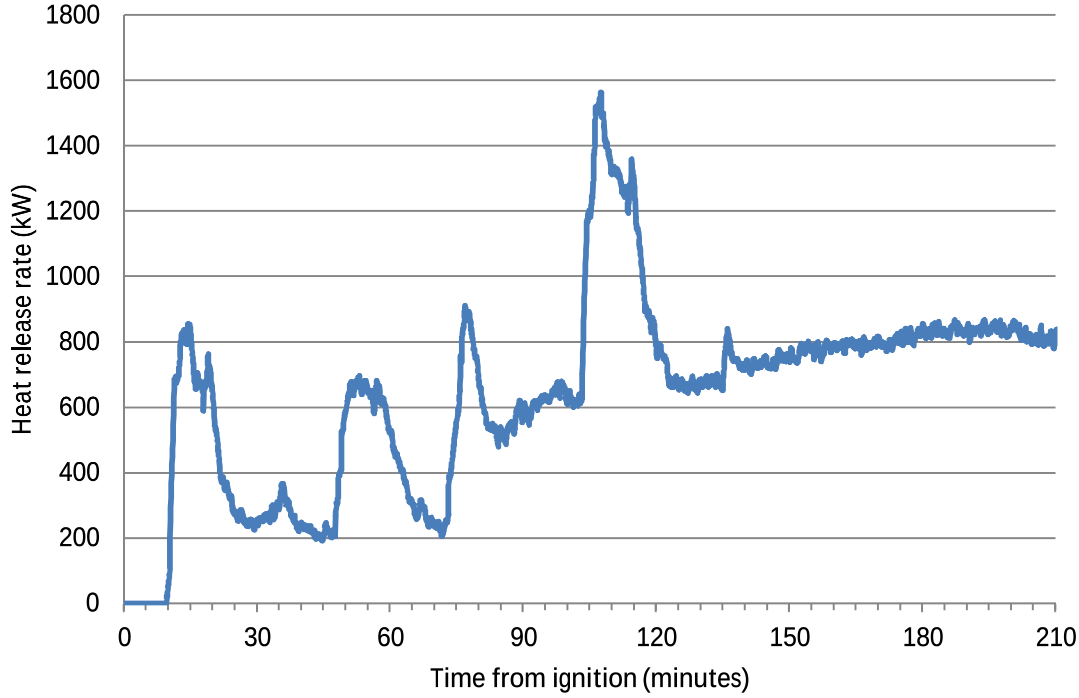


Figure 155 – Heat release rate data during Reconstruction 1

3.2.2.2. Reconstruction 2 and Results

Following the completion of Reconstruction 1 it was agreed that a second reconstruction would be carried out to examine the effect of a different fuel load on the development and growth of the fire. It was originally intended to force ignition of additional pallets after 60 minutes, but this was not required as fire spread occurred without the need for any intervention.

Observations compiled from the analysis of the video footage of the reconstruction fire are presented in Table 27.

Time from ignition (hours: minutes: seconds)	Notes
00:00:00	Apply flame to back of pallet A to start ignition
00:00:32	Remove flame
00:01:05	Right hand box, back of pallet A begins to open
00:01:22	Right hand box, back of pallet A; side folds down, fire almost goes out
00:02:03	Right hand box, back of pallet A centre involved (fire growing)
00:03:06	Top box of pallet A ignited
00:06:08	Top of box on top of pallet D begins to lift due to heating. Wrap on pallet C begins to shrink
00:06:25	Front right hand box on pallet A slumps
00:06:53 (approx.)	Long flames lean into centre of rig
00:07:37	Flames extending in excess of 1m above top of boxes
00:07:44	Contents of left hand box of pallet A collapse into centre
00:08:44	Collapse on right hand side of pallet A
00:08:56	Top of box at back of pallet D fully lifted. Wrap well shrunk on pallet C.
00:09:02	Collapse on right hand side of pallet A

Time from ignition (hours: minutes: seconds)	Notes
00:09:04	Top of box at back of pallet D begins to lower
00:25:11	Front left boxes on pallet A collapse forward
00:53:29	Flames from underside of pallet A
00:53:54	Roll of labels on right hand side of pallet A smoking
00:54:01	Flames from underside of pallet A extend well into centre
00:54:28	Debris on right hand side of pallet A alight
00:54:54	Boxes on right hand side of pallet B scorched, tape melting
00:56:40	Pallet B pyrolysing
00:57:14	Pallet B spontaneous ignition
00:57:29	Pallet B rear two stacks of boxes involved over full height
00:57:40	Collapse into centre from pallet A
00:57:41	Paint on right hand wall cracked and glowing
00:57:41	Pallet B collapses backwards, setting fire to wrapped pallet C
00:57:53	Right hand side wall smoking
00:58:12	Boxes on pallet D well alight
00:58:18	Pallet B collapses backwards
00:58:18	Further collapse of pallet B
00:58:41	Smoke from left of pallet B boxes
00:58:54 (approx.)	Dark smoke
00:59:13	Pallet B collapse to centre
00:59:15	Pallet B collapse backwards
00:59:16	Spark falls from floor to laboratory floor
00:59:27	Continual drip of sparks falling from floor, causing development of fire on ground level
00:59:46	Collapse at back of pallet D backwards off of floor onto laboratory floor
00:59:54	Paint on left hand side wall burns
00:59:58	Collapse on left hand side of pallet B
01:00:30	Left hand side wall on fire
01:00:32	Collapse on left hand side of pallet B
01:00:35	Ceiling alight
01:00:52	Right hand side wall on fire
01:01:45	Roll of labels fall off floor forwards
01:01:56	Water on

Table 27 – Significant observations from video footage of Reconstruction 2

The temperature data obtained from thermocouple trees A and B are given in Figure 156 and Figure 157. The temperature data obtained from thermocouple trees C and D are given in Figure 158 and Figure 159.

From Figure 156, it can be observed that from thermocouple tree A show an initial 50 minute phase of burning that is very consistent with that from Reconstruction 1. Around 53 minutes into the fire, the temperatures start to increase until there is ignition of the boxes containing the plastic materials and a rapid increase in all temperatures up to a peak around 930°C.

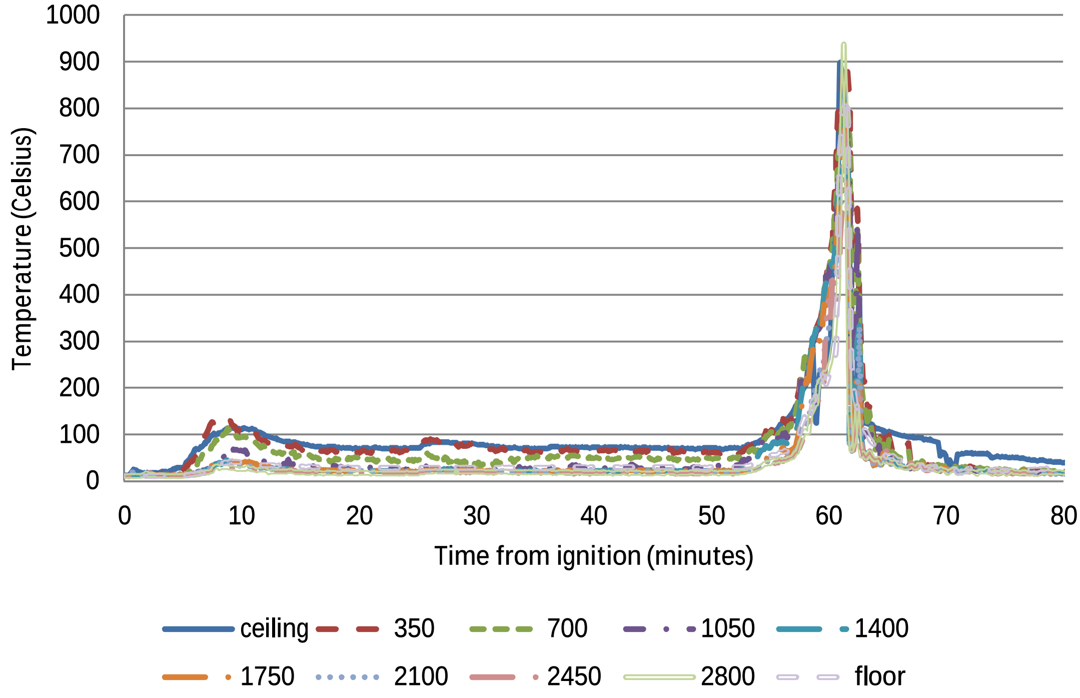


Figure 156 – Temperature data at thermocouple tree A during Reconstruction 2

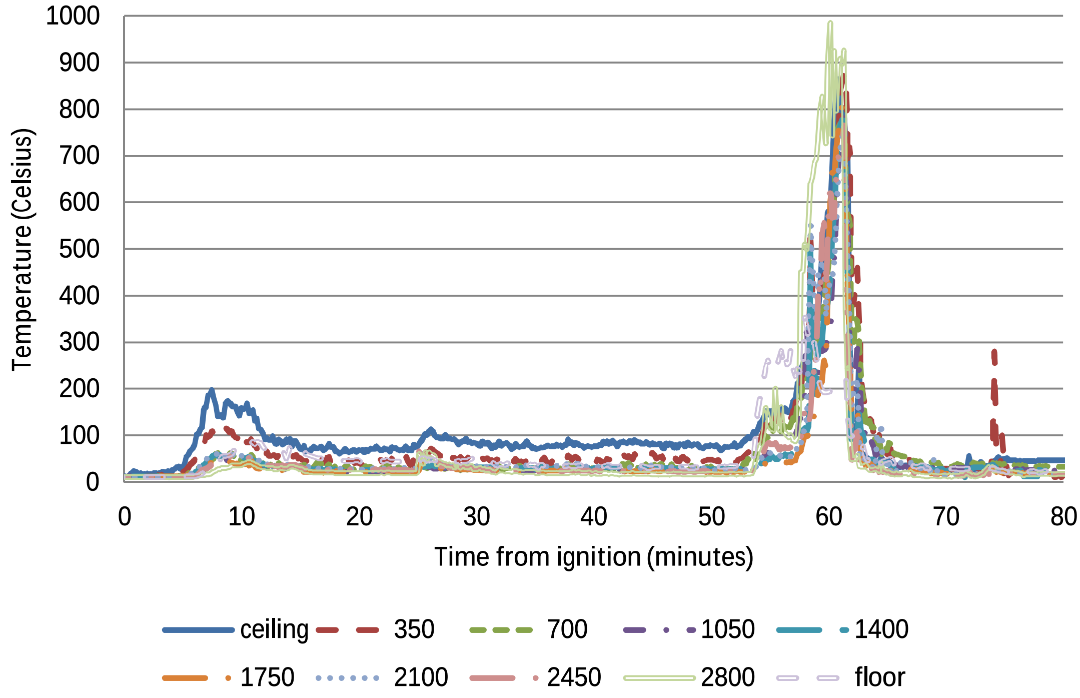


Figure 157 – Temperature data at thermocouple tree B during Reconstruction 2

Temperatures at thermocouple tree B show temperatures that are also very similar to those from Reconstruction 1, but with less noise. As with thermocouple tree A, around 53 minutes into the fire, the temperatures start to increase until there is ignition of the boxes containing the plastic materials and a rapid increase in all temperatures up to a peak around 950°C.

Thermocouple trees C and D measured temperatures that were consistent with the temperatures measured by thermocouple trees A and B. As with thermocouples trees A and B, peaks and troughs in the data recorded from thermocouple trees C and D correspond well with events that lead to the major peak in the data at around 60 minutes. The temperature data obtained from thermocouple trees C and D are given in Figure 158 and Figure 159.

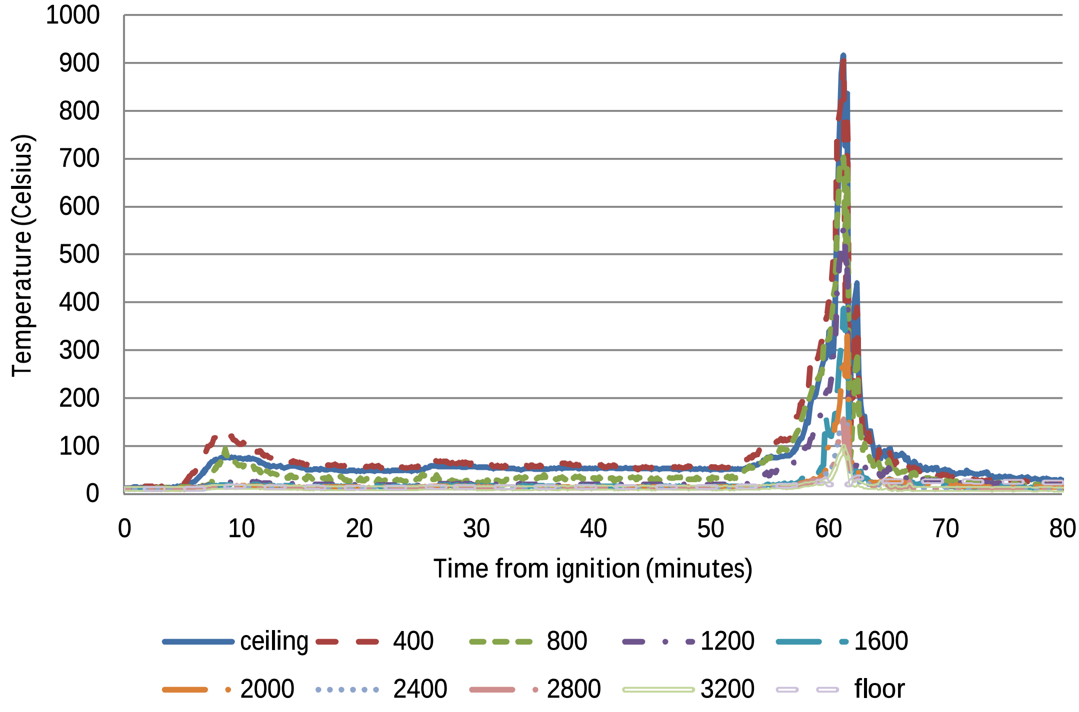


Figure 158 – Temperature data at thermocouple tree C during Reconstruction 2

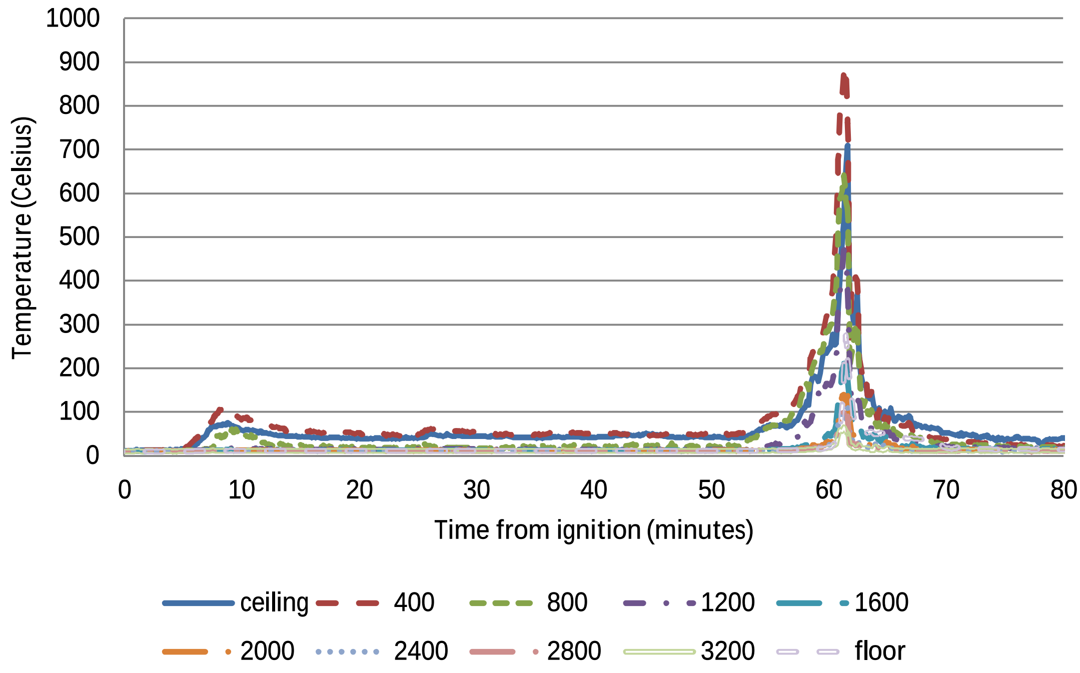


Figure 159 – Temperature data at thermocouple tree D during Reconstruction 2

The thermocouples installed in the ceiling void show a gradual increase in temperature throughout the reconstruction, with a marked increase in temperatures occurring during the sudden period of fire growth when all temperatures inside the room and corridor increased suddenly, see Figure 160. This period coincides with the period when the heat release rate of the reconstruction fire is at its greatest, shown later in Figure 163.

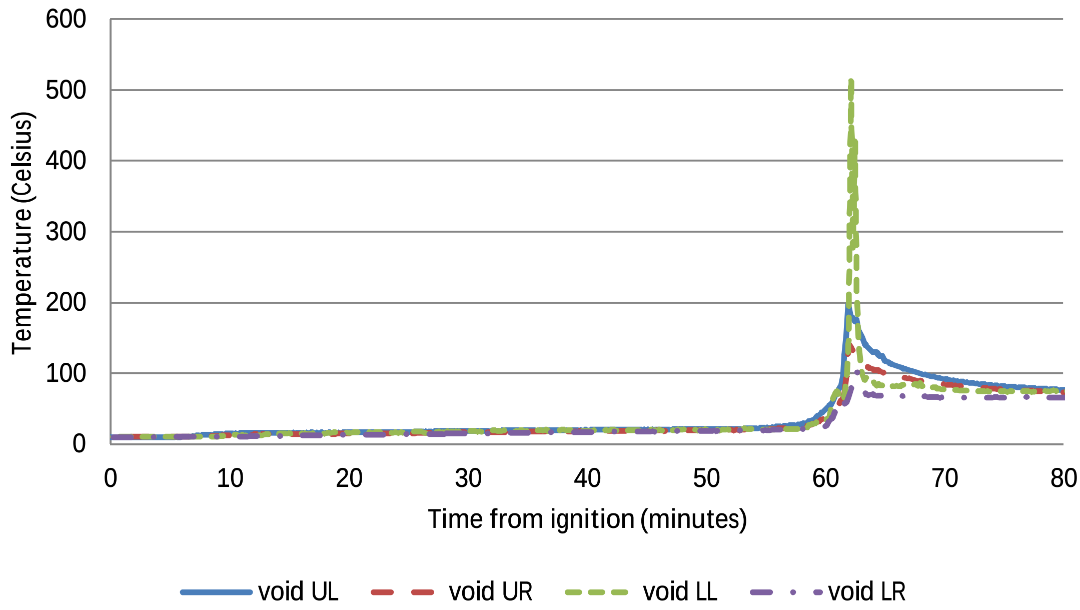


Figure 160 – Temperature data at thermocouples located in ceiling void during Reconstruction 2

The thermocouples installed on the upper and lower surfaces of the floor show temperature increases that are dominated by the spread of fire through the fuel bed on top of the floor; the upper surface nearest the ignition pallet is consistently warmer than the other three measuring locations on the chipboard floor for the first 50 minutes. There is a significant increase in upper surface temperatures (indicating involvement of the floor and flashover) during the sudden period of fire growth. There are also significant, albeit not as sudden, increases in the temperatures of the lower surface of the chipboard at this time. The data collected from these thermocouples can be seen in Figure 161.

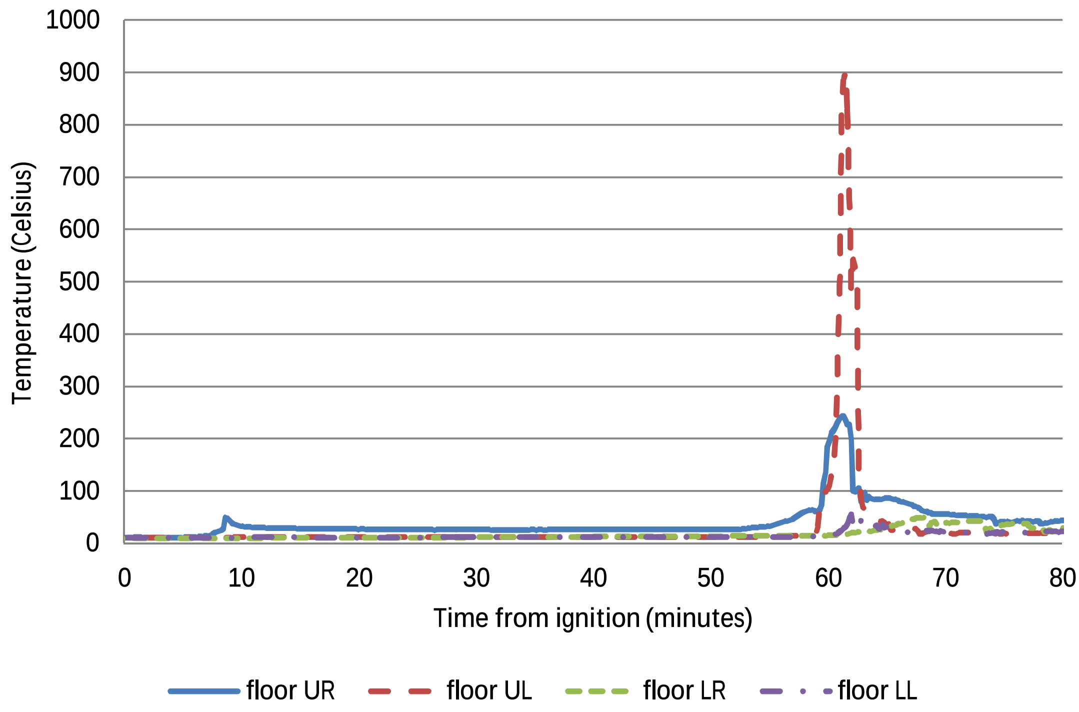


Figure 161 – Temperature data at thermocouples located on upper and lower surfaces of suspended floor during Reconstruction 2

The heat flux meter data collected are presented in Figure 162. The data show a relatively steady increase in heat flux as the fire has developed until the period of sudden fire growth. As with Reconstruction 1, there is a marked difference between the 2m (near) and 4m (far) heat flux meters which, which may be due to the 2m heat flux meter 'seeing' the flames from the fire (i.e. the flames from the fire were within the viewing aspect of the heat flux meter). The 4m heat flux meter has a sudden peak of measured heat flux shortly after the period of sudden fire growth. This may be due to re-ignition of fire gases in the corridor above the heat flux meter; although no camera footage was able to confirm it.

The calorimetry data collected from Reconstruction 2 reflect the findings detailed so far. There is a major peak around 61 minutes after ignition, which is a result of the involvement of all of the combustible material in the room, including the chipboard floor, indicative of flashover. Significant events considered likely to account for these peaks are marked on Figure 163.

Over the duration of Reconstruction 2, the 9m calorimeter, measuring heat release from smoke exiting the corridor of the rig, registered one main peak of 14.9 MW.

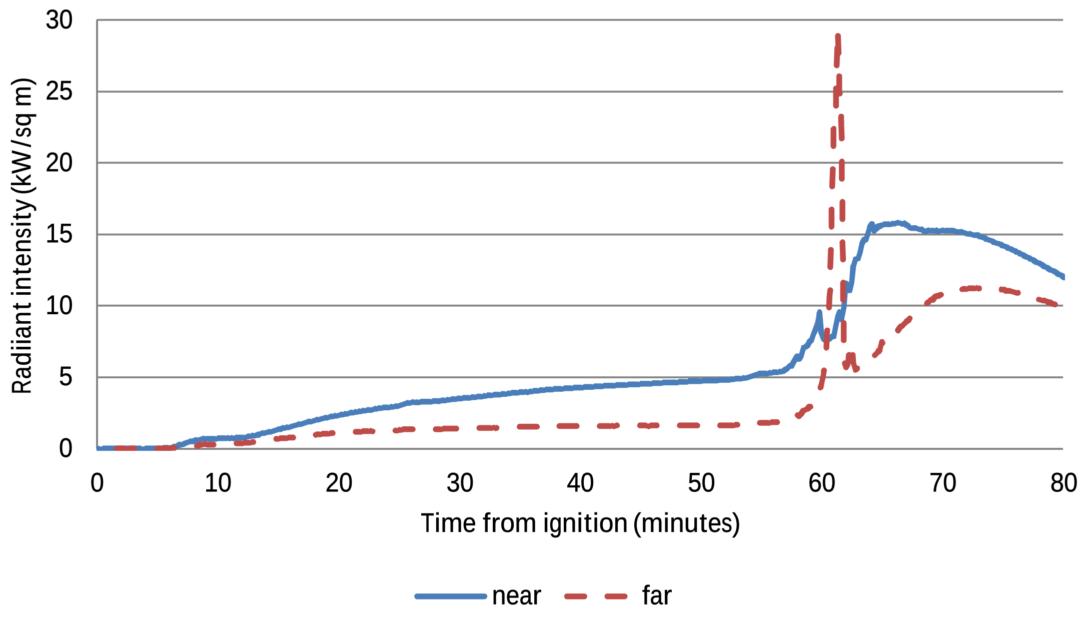


Figure 162 – Radiant heat fluxes measured at floor level inside the corridor 2m (near) and 4m (far) away from the front edge of the room during Reconstruction 2

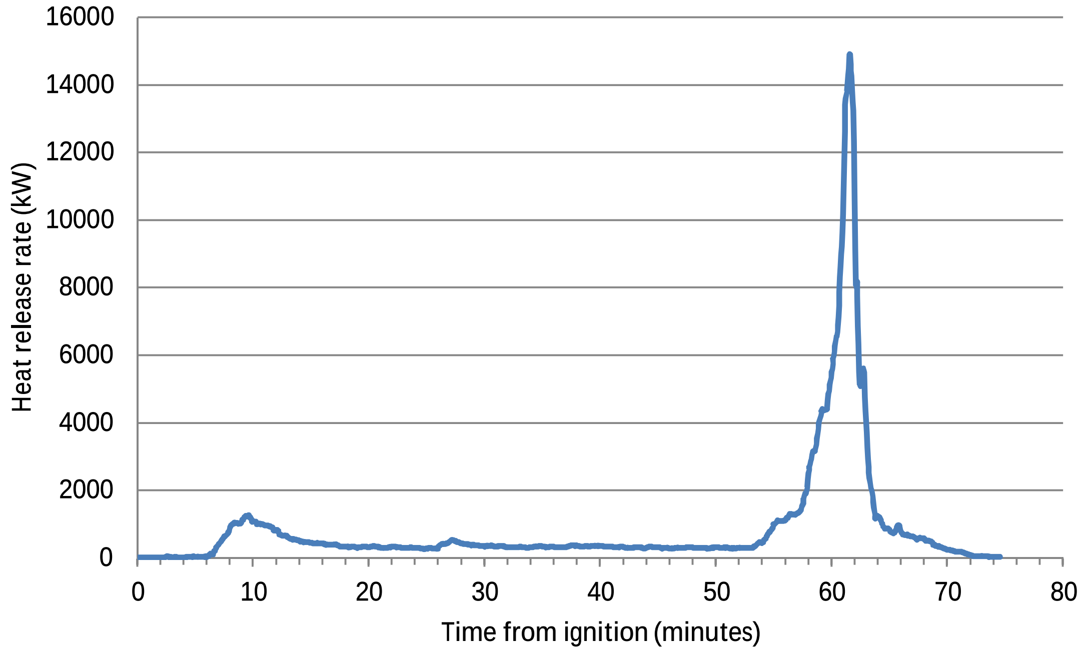


Figure 163 – Heat release rate data during Reconstruction 2

3.2.2.3. Observed Differences between Reconstruction Fires and Incident

As previously mentioned it was neither possible nor expected to fully re-create the fire that occurred during the incident at Wealmoor Atherstone. The extent of the rig was clearly far less than that of Wealmoor Atherstone. The data generated during the reconstructions was therefore taken forward to be included in computer modelling.

The fuel load present in Reconstruction 1 did not lead to the development of a fire that appears to be consistent with the fire that occurred in Wealmoor Atherstone, even considering the reduction in scale. Temperatures achieved in Reconstruction 1 were not sufficient to account for the extent of damage that occurred at Wealmoor Atherstone. It is likely that the way in which Reconstruction 1 occurred was a result of the energy release rate being insufficient to exceed the rate at which energy was lost from the environment of the reconstruction (i.e. heat was being lost from the rig faster than the fire could produce more heat).

Reconstruction 2 appears to have produced a sequence of fire growth and development that is more consistent with the observations made at Wealmoor Atherstone. An initial phase of relatively minor burning, similar to Reconstruction 1, occurred for the first 50 minutes followed by a sudden increase in heat release rate, which led to the reconstruction needing to be terminated for safety reasons. The runaway increase in heat release occurred as a result of the energy being released by the fire into the rig far exceeding the capacity of the rig to dissipate heat. The excess heat within the rig was fed back into the fire and surrounding fuel, which then further increased the rate of heat release, leading to the runaway increase in fire size that was observed and measured.

3.2.3. **Bench Scale Tests on Chipboard Floor**

As previously discussed, there was conflicting information concerning the contents that were in the area of origin of the actual fire. However, it was known that there was a significant quantity of fuel in Atherstone represented by the chipboard flooring alone. Tests were therefore carried out to further investigate the properties of the chipboard floor and any potential implications that this might have had for the development of the fire during the incident. The tests that were carried out were the ISO 5660 Cone Calorimeter test and a BS 476 Part 7 surface spread of flame test.

3.2.3.1. Properties of Flooring

The flame spread model that would later be used by JASMINE (the work of Richard Chitty) to simulate the fire behaviour of the chipboard floor, used a combination of manufacturer's data and data derived from standard cone tests on the material.

The published density of the floor material is 622kg/m^3 and the board thickness was 38mm. This gives a mass per unit area (as required by JASMINE) of 23.6 kg/m^2. A typical value of 0.14W/m/K was used for thermal conductivity.

The value of specific heat capacity was derived from the cone data and the above values for density and thermal conductivity.

Plotting the radiation intensity against the reciprocal of the square root of the time to ignition gives a linear plot, which can be used to find the thermal property kρc and the critical radiation intensity. The data from the cone tests carried out on the chipboard are shown in Figure 164 and Figure 165.

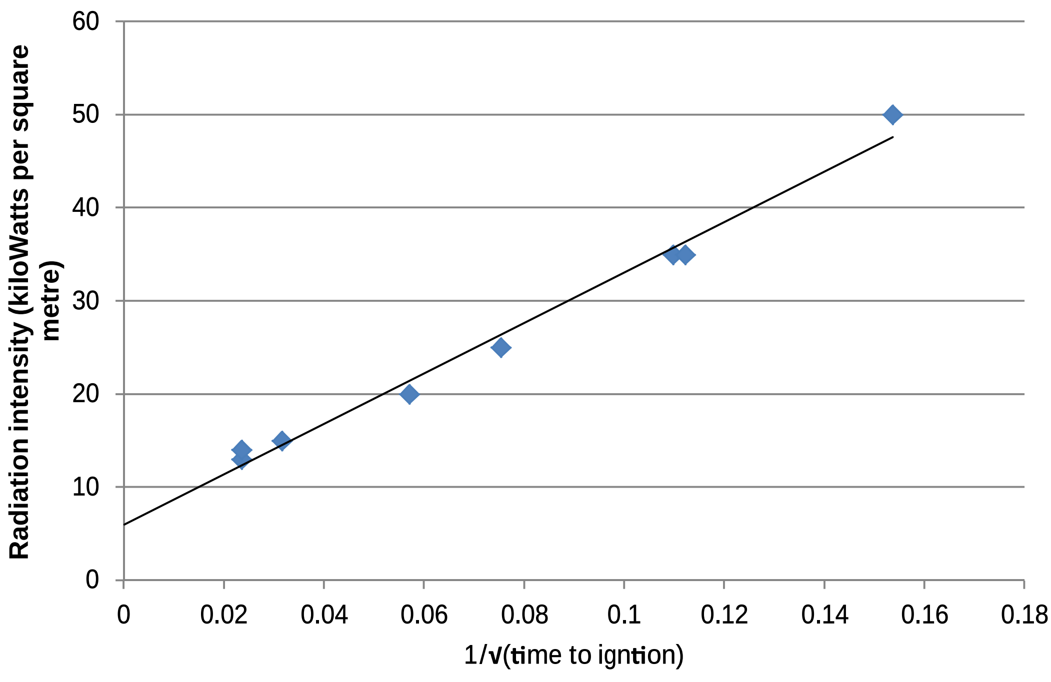


Figure 164 – Critical irradiance plot from cone calorimeter tests on particle board flooring

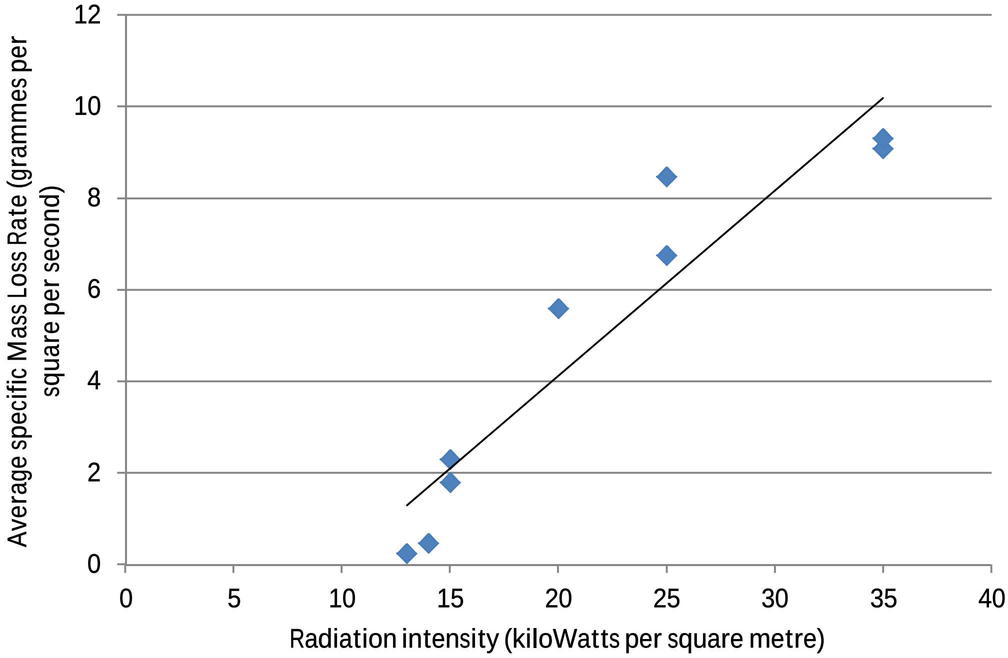


Figure 165 – Average mass loss rate plot from cone calorimeter tests on particle board flooring

From Figure 164 the critical radiation intensity for ignition is found from the intercept with the x-axis (when $t^{-1/2}=0$). Using the regression line through the points this gives a value of 5.6 kW/m^2. If it is assumed that the material is thermally thick, i.e. there are no heat losses from the unexposed side during the test, then the slope of the regression line is related to the thermal inertia kρc by:

$$slope = \frac{\epsilon}{\sqrt{\frac{2k\rho c}{3}}\left(T_{ig} - T_o\right)} \tag{12}$$

The ignition temperature is found from

$$q_{crit} = \frac{1}{\varepsilon}\left(h\left(T_{ig} - T_o\right) + \epsilon\sigma T_{ig}^4\right) \tag{13}$$

The equation was evaluated for several values of ignition temperature and it was found a temperature of 230°C corresponded to 5.6kW/m^2assuming an emissivity of 1. The regression line on Figure 164 has a slope of 280 that gives a value of kρc of 2.2 $kW^2sm^{-1}K^{-2}$.

From the values of k and ρ, the calculation gives a value for specific heat capacity of 25000 J/kg/K. It should be noted that this is not the thermal property of the material but an equivalent value including chemical processes that occur as the material is heated prior to ignition. A more “reasonable” value (based on published data) of 2400kJ/kg/K is used in the simulation for heating of the material. The additional energy implied above (i.e. the large difference between 25000 and 2400 J/kg/K) is accounted for by the critical energy the material needs to accumulate before ignition.

3.2.3.2. Comparing Bench Data with Reconstruction Data

Figure 165 shows the average mass loss rate measured in each test plotted against the radiation intensity. The slope of the regression line of these data is a function of the heat of pyrolysis of the material.

$$L = \frac{1}{slope} \tag{14}$$

This gives a heat of pyrolysis of 2.5MJ/g for the floor material. Integrating the rate of smoke production gives the total quantity of smoke produced this is shown in Figure 166.

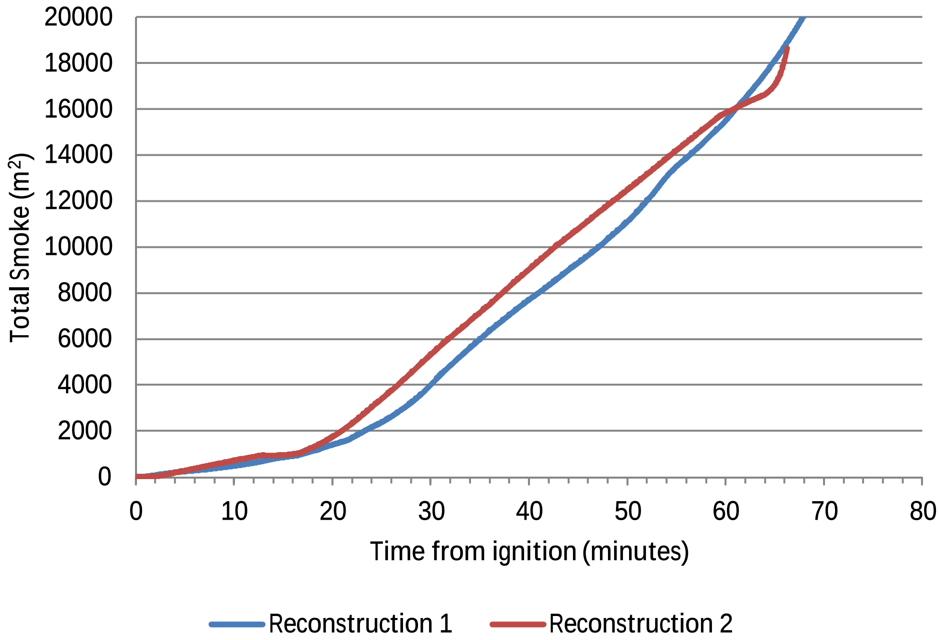


Figure 166 – Total quantity of smoke produced

If all the smoke from a test is contained in a large volume then the visibility in that volume can be estimated. However this involves several assumptions. Over a long period of time (tens of minutes) smoke particles will “fall out” of the gas, either by adhering to walls and other objects or colliding with other smoke particles and coagulating into larger particles that are too heavy to remain suspended in the gas. The volume occupied by the smoke will also depend on whether a distinct smoke layer is formed or if the smoke is uniformly mixed throughout the whole space. Finally visibility depends on lighting conditions. There is correlation relating smoke concentration to visibility of reflecting and illuminated signs.[154]

3.2.4. **Computer Modelling Review**

This section (3.2.4) summarises the key findings of work carried out by Richard Chitty of BRE (i.e. computer modelling). Full details of the work carried out can be found in BRE report number 275178.[153]

3.2.4.1. Heat Release Rate

Predicting the heat release rate of a fire is one of the challenges of fire modelling. The approach used for this investigation has been to use the measured heat release rate for a single stack of goods and apply that growth rate to each of the stacks in the enclosure. To account for the effect of one burning stack enhancing the burning rate of its neighbours, the measured burning rate is multiplied by a factor depending on the thermal radiation feedback. The burning of the floor is simulated using a simple pyrolysis model with material data derived from standard small scale tests (cone calorimeter and spread of flame tests, see above).

Figure 167 shows the measured heat release rate for Reconstruction 1 and 2 during the first 30 minutes after ignition. The ignition times of the two reconstructions have been aligned using the time where the heat release rate in each reconstruction reaches 50kW (Reconstruction 1, 15 minutes, Reconstruction 2, 11.2 minutes).

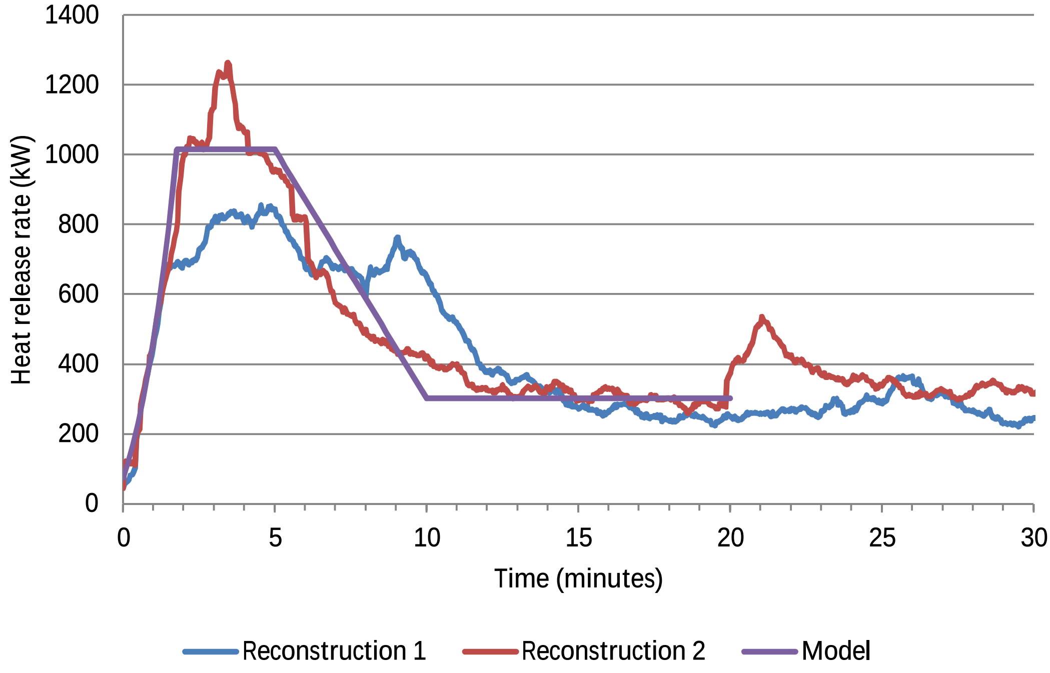


Figure 167 – Comparison of the heat release rates with aligned ignition times for the reconstruction fires and the "model"

3.2.4.2. Modelling Approach

All the computer simulations for this investigation have used the BRE Global CFD (computational fluid dynamics) program JASMINE. The CFD methodology was selected because of the large floor area and need to include the under floor void. The simpler zone models would not be valid for this configuration.

Due to the long duration of the period of interest during the actual fire; from approximately 17:15 to approximately 19:30 it was impractical to run continuous computer simulations for the whole incident. This would have required several months of computer time. To resolve this, two distinct stages during the fire were identified and simulated independently both for the reconstruction and the incident. The simulations of the reconstructions were also used to validate the use of the program. The simulations are outlined in Table 28.

Scenario number	Simulation	Objective
1	Steady state simulation of reconstruction fire using heat release rate data between 15 and 30 minutes from Figure 167.	Compare temperatures to show there is a reasonable representation of the fire source and the material properties give the correct heat losses to the structure.
2	Transient simulation of flashover event in Reconstruction 2.	Examine mechanisms and criteria for flashover; demonstrate this can be simulated reasonably realistically.
3	Incident simulation of smoke filling.	Predict conditions in first floor storage area during initial investigation and search of the area.
4	Incident simulation of flashover in pallet bay.	Predict fire growth in redundant stock bay and consequential change of conditions in the rest of the first floor storage area.
5	Additional ventilation.	Examine influence of additional ventilation (open doors and open construction) to first floor conditions.

Table 28 – Modelling scenarios

The first two simulations were intended to establish how to perform the simulations, determine material properties and demonstrate, by comparison with the measured reconstruction data, that the approach would be reasonably accurate. The remaining three simulations applied the computer modelling approach to the Atherstone incident.

3.2.4.3. Scenario 1 – Reconstruction 1

The JASMINE predictions for Scenario 1 confirmed that the fire heat release rate for the initial burning pallet were a reasonable representation of the reconstruction fires. In addition the close agreement of the temperature data indicates that the heat losses to the structure (and hence the materials properties) are reasonably represented. The opening at the back of the compartment may have kept the flames on the pallet A upright. If the flames had lent towards the back of the compartment this would have increased the radiation to pallet D.

3.2.4.4. Scenario 2 – Reconstruction 2

The reconstruction data and computer simulations indicate that the compartment reached a point where the fire would rapidly grow to involve all the combustible surfaces when the layer temperature was approximately 400°C. This temperature corresponds to a maximum radiation intensity of $11kW/m^2$ from the layer. This would have been enhanced by radiation from the flames on the burning pallets. It was assumed due to the confined space that pilot ignition would be possible either from burning brands or flames from the burning pallets and collapsed debris. The temperature of 400°C in the experimental rig appears to be a “point of no return” beyond which all the exposed material in the rig would have ignited by pilot ignition from brands and burning debris fallen from the pallets.

Temperatures of 550°C to 600°C are often quoted for the onset of flashover[18,19]. These temperatures correspond to a radiation intensity of approximately 25kW/m^2, which is sufficient for spontaneous ignition of most combustible materials. During Reconstruction 2, these temperatures were reached within a minute of the temperature exceeding 400°C.

The predictions of heat release rate confirm the assumption of using an ultra fast growth rate to simulate the initial burning of a pre-heated pallet during the development of the fire to flashover.

3.2.4.5. Scenario 3 – Incident Simulation of Smoke Filling

The simulations of the incident were run using a geometry that represents the first floor of Atherstone, as shown in Figure 168.

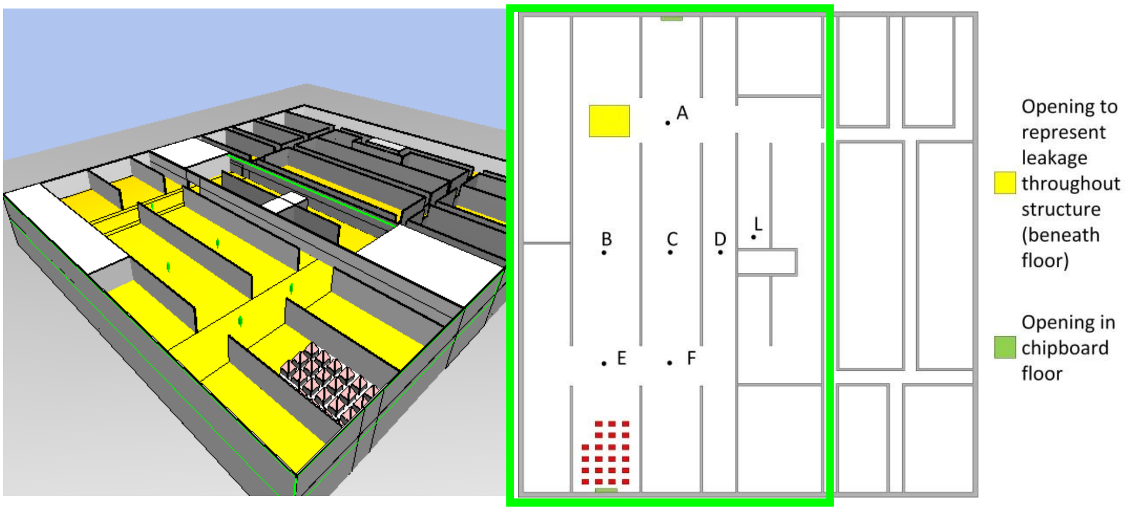


Figure 168 – Geometric model of first floor storage area. The green box indicates the extent of the calculation domain

The simulations of the first floor of Wealmoor Atherstone indicate that a fire involving a single pallet, demonstrated by the reconstruction fires as being plausible for some considerable time, would have caused a gradual worsening of visibility throughout the storage area compartment. However, the worsening in visibility would not necessarily have been accompanied by any significant increase in temperatures. Figure 169 and Figure 170 show the predictions of temperature and visibility at head height (1.7m above floor) and low (0.5m above floor) levels.

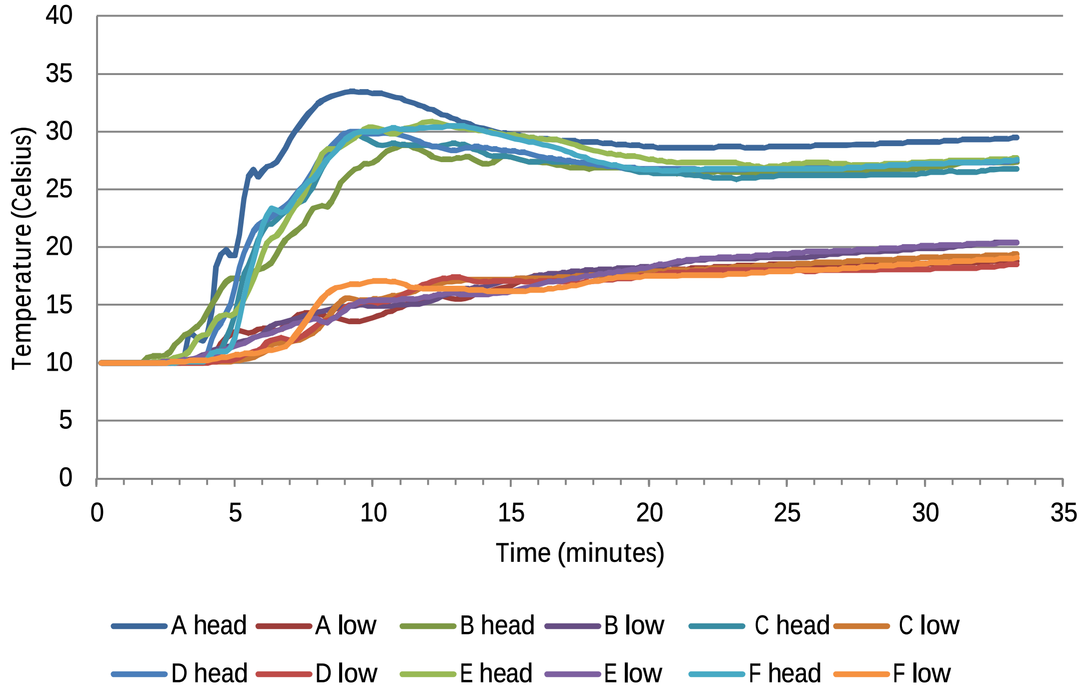


Figure 169 – Predictions of temperature in first floor storage area at the locations shown on Figure 168

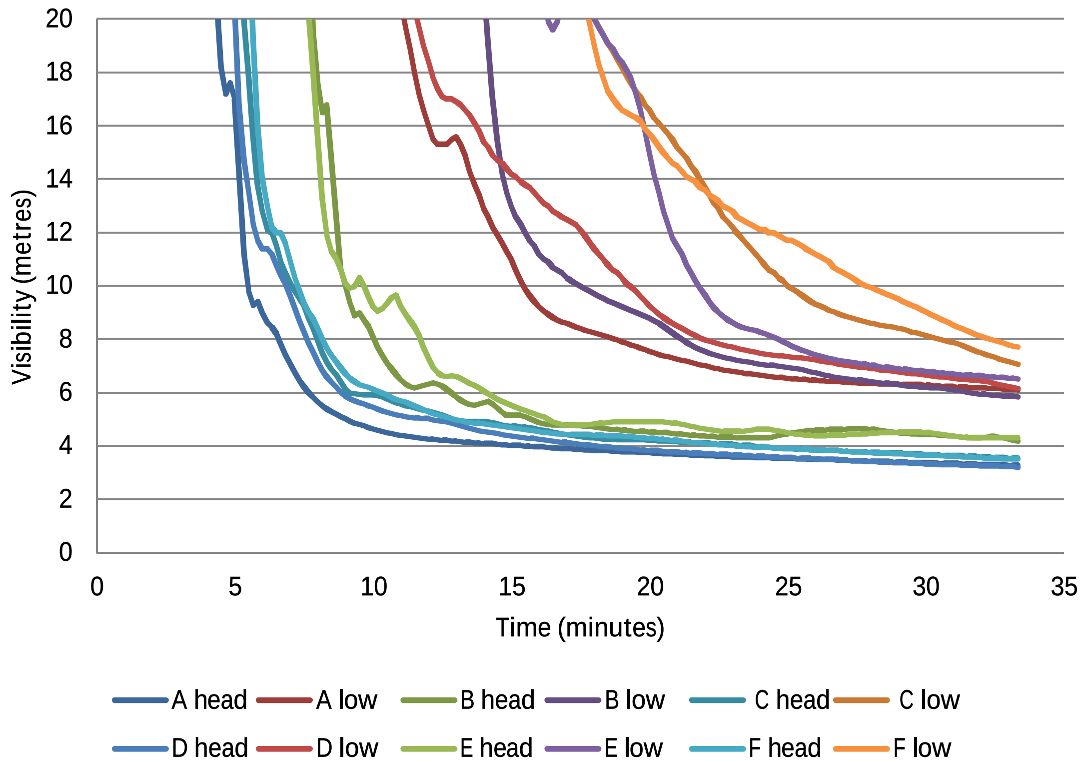


Figure 170 – Predictions of visibility in first floor storage area at the locations shown on Figure 168

Within the 35 minute time period that it has been possible to compute, the simulation has shown that visibility at head height would drop to less than 4m and that temperatures would only increase a few degrees above ambient. This is consistent with descriptions in the incident timeline of smoke 'just hanging in the air around the building'. Smoke only rises when its temperature is above that of the surrounding air.

3.2.4.6. Scenario 4 – Incident Simulation of Flashover in Pallet Bay

The analysis of Scenario 2 concluded that a layer temperature of 400°C would provide sufficient radiation onto the exposed material to be sufficient for piloted ignition. Due to the proximity of the pallets, the likelihood of ignition from a burning brand or direct flaming from burning debris would be high.

The development of the fire was modelled starting from the conditions predicted by Scenario 3 after 600 seconds when the first floor storage area is filled with smoke. It was then assumed that pallet 8 (primary pallet) collapsed and burning material reaches and ignites the surrounding pallets (1, 2, 3, 9, 15, 14, 13, and 7) (secondary pallets) which begin to burn following an ultra fast growth, limited to 1.5MW, as used in Scenario 2. The remaining pallets (tertiary pallets) ignite when the radiation intensity reaches $10kW/m^2$. Sections of the floor at the front of the redundant stock bay and in other parts of the first floor store ignite after receiving a fixed amount of energy by radiation, in excess of the critical radiation intensity of $5kW/m^2$ as in Scenario 2.

Note that the remainder of the geometry used in the modelling does not contain any combustible contents other than the chipboard floor. Given the uncertainty concerning the specific contents in the various parts of Wealmoor Atherstone, it was decided to exclude the contribution that any of these materials might have made to the development of the fire. Assuming that any such contents would be as susceptible to ignition and burning as the chipboard floor, if not more so, then the inclusion of any such materials would be expected to make the fire grow more quickly. This is due to the presence of any additional material effectively moving the combustible surface higher up and closer to the hot smoke layer and downward radiation. The modelling approach that was used here is therefore considered to have provided a conservative representation of the severity of the fire development that occurred in the incident.

3.2.4.7. Scenario 4 Results

The first tertiary pallet ignited 1 minute after the ignition of the secondary pallets and the remaining tertiary pallets ignited in the following 30 seconds. The front floor of the redundant stock bay ignited after 3 minutes and the floor material in the first floor storage area began to ignite after 4 minutes.

Figure 171 shows the predicted temperature at the six locations shown in Figure 168 at head height (the time scale begins with the ignition of the secondary pallets). This shows the temperature at all the locations starting to rise when the tertiary pallets ignite.

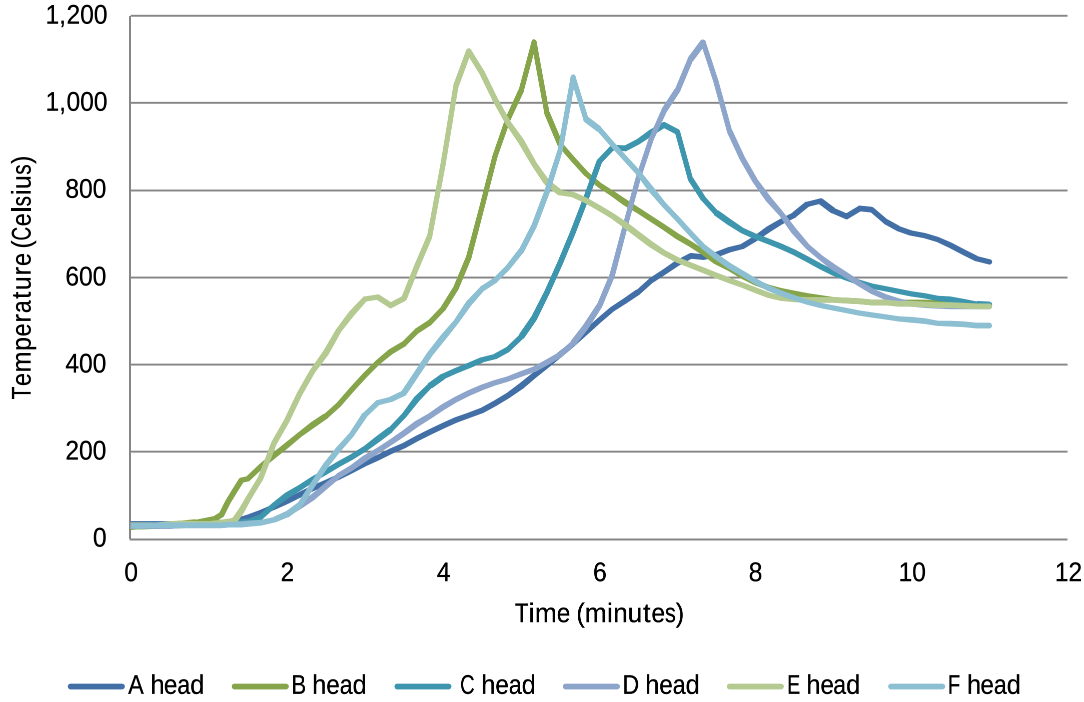


Figure 171 – Temperature predictions for Scenario 4 at head height at the locations shown on Figure 168. Note that time zero does not relate to the first ignition during the incident, but to the ignition of the secondary pallets

The peak temperatures at each location occur at a different time as the fire propagates through the first floor storage space. After the temperatures peak, the temperatures fall due to the local lack of oxygen, but remains at a high value (>500ºC) because of the highly insulating properties of the compartment walls.

Figure 172 and Figure 173 show temperature contours at head height in the first floor storage area. As with Figure 171, note that time zero relates to the ignition of the secondary pallets, not the ignition of the first pallet.

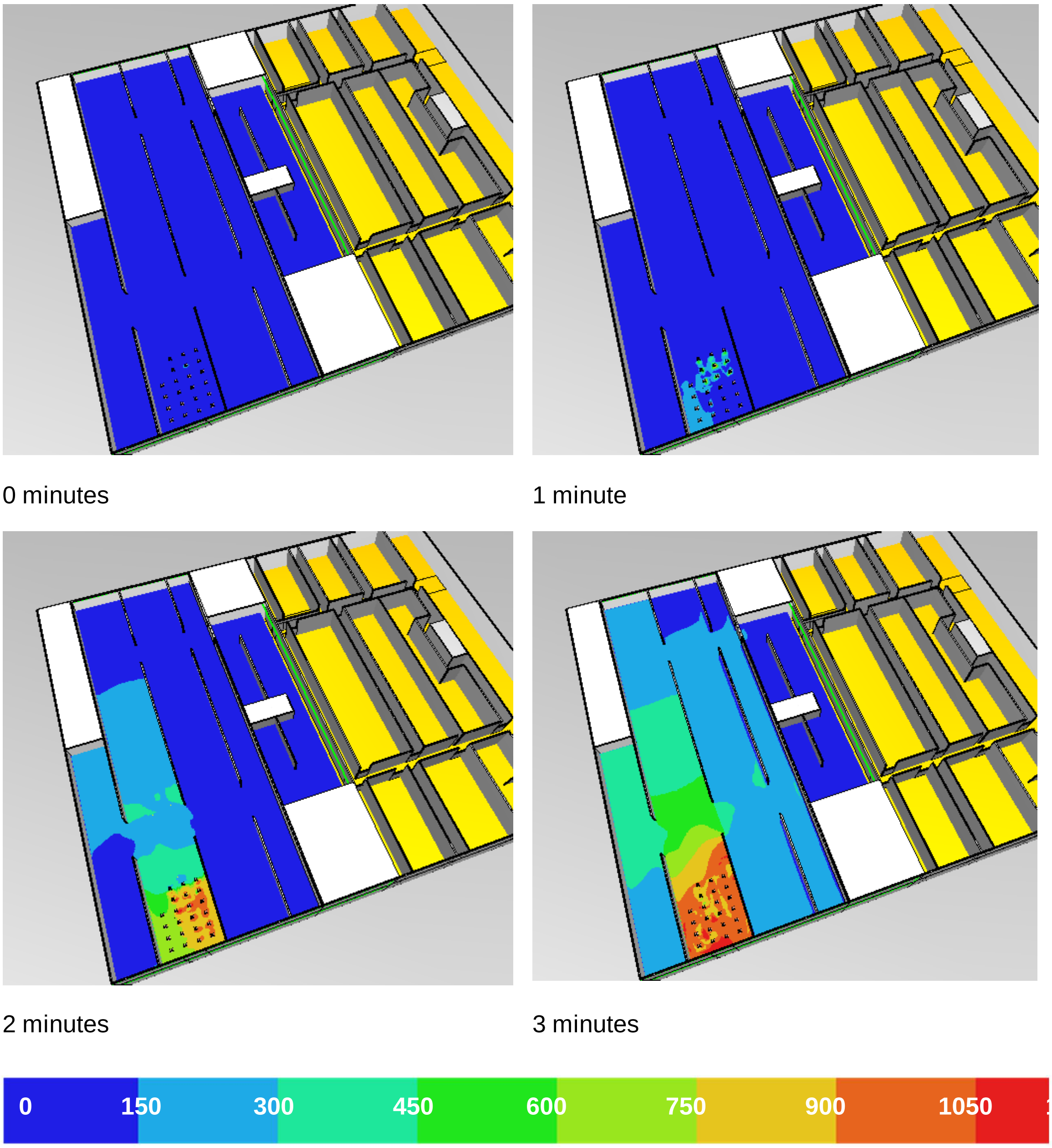
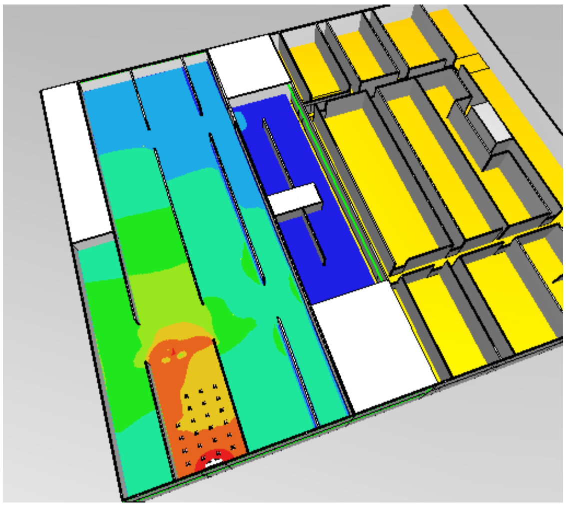
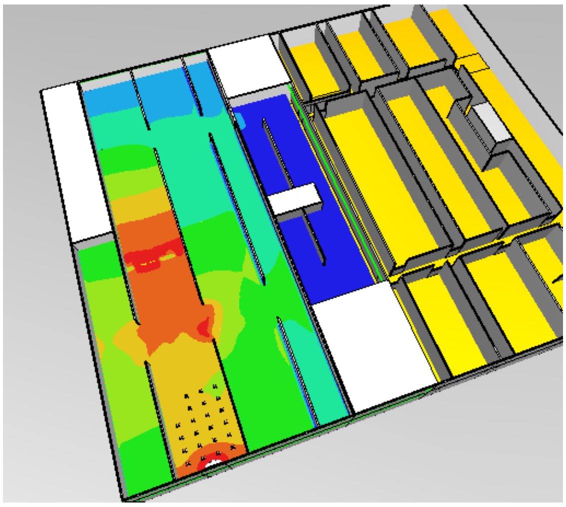


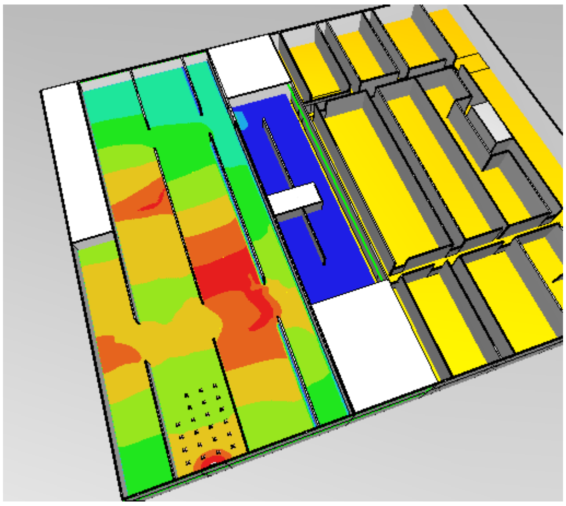
Figure 172 – Contours of temperature predictions for Scenario 4; horizontal section at head height in Section B and lift lobby



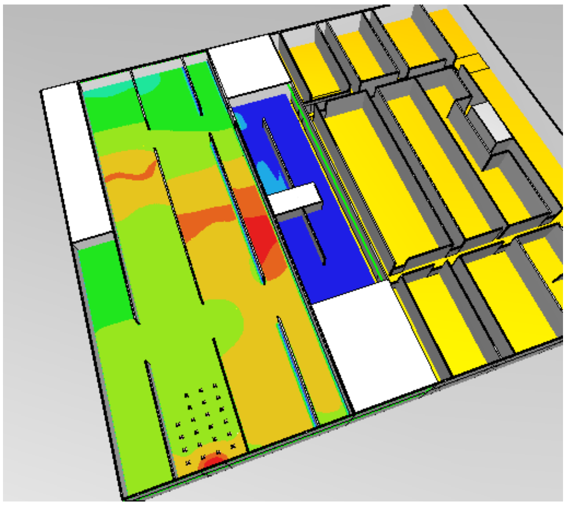
4 minutes



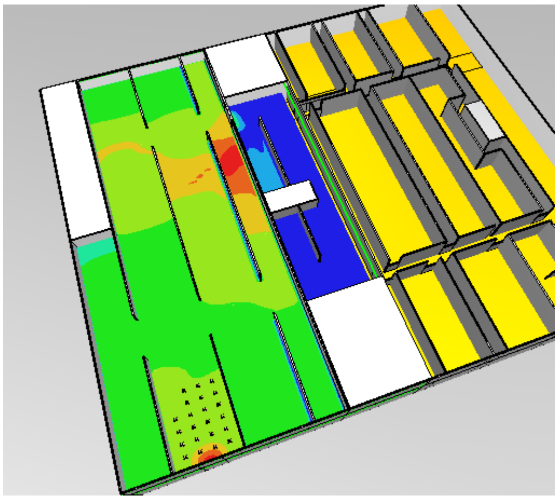
5 minutes



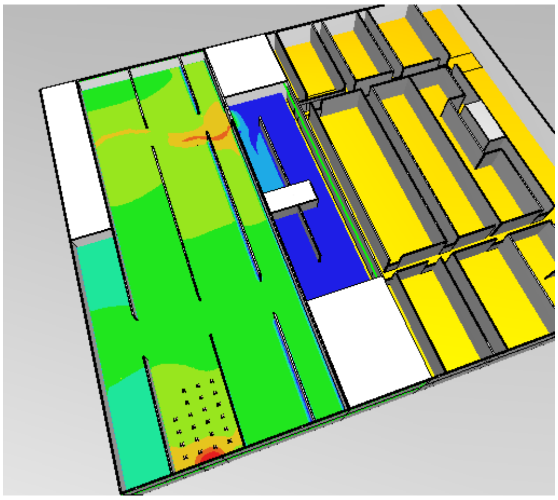
6 minutes



7 minutes



8 minutes



9 minutes

Figure 173 – Contours of temperature predictions for Scenario 4; horizontal section at head height in Section B and lift lobby

Figure 172 and Figure 173 show a very hot burning zone propagating through the first floor storage area, this leaves behind a region with very low oxygen concentration. When the burning region reaches the location of the hole in the four hour wall, the fire is maintained by air from the rest of the upper floor.

Figure 174 shows the predicted heat release rates for Scenario 4. During the rapid development of the fire, there is a strong outflow of smoke and hot gases from the first floor store into the lift corridor and the rest of the building. Figure 175 shows the velocity of these gases at the opening in the four hour wall between the first floor storage area and the lift lobby. Up to 6 minutes there is only an outflow, so no additional oxygen enters the first floor storage area up to this time.

Figure 176 shows the temperatures and visibility at location L (see Figure 168) within the lift lobby. Figure 177 shows the temperatures and visibility at the opening in the four hour wall between the first floor storage area and the lift lobby.

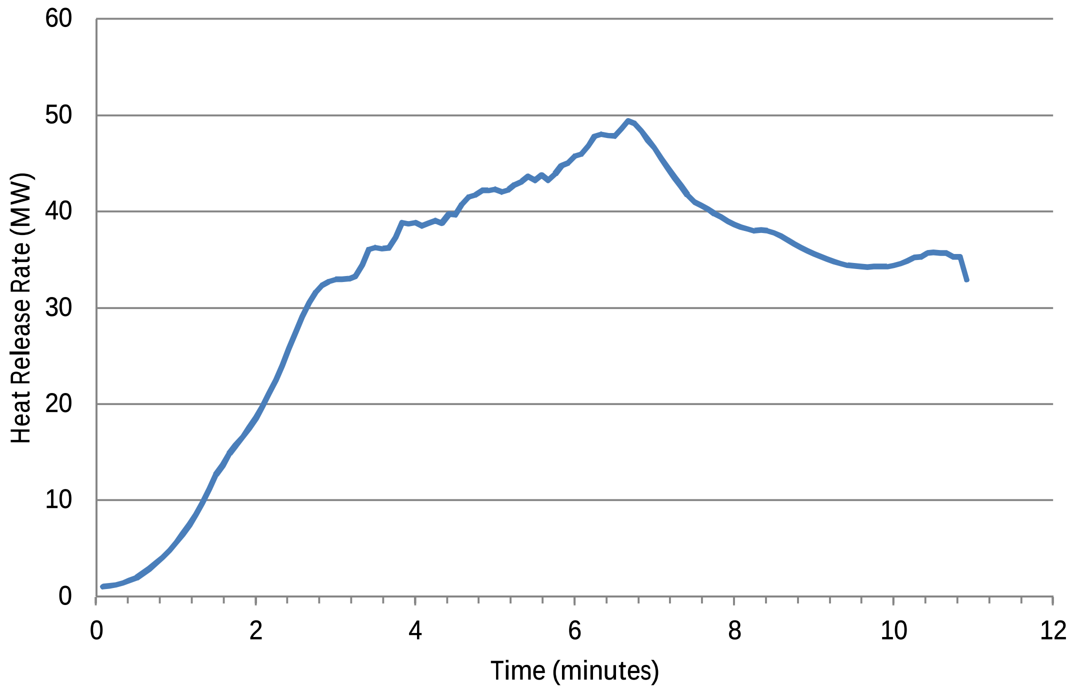


Figure 174 – Total heat release rate for Scenario 4

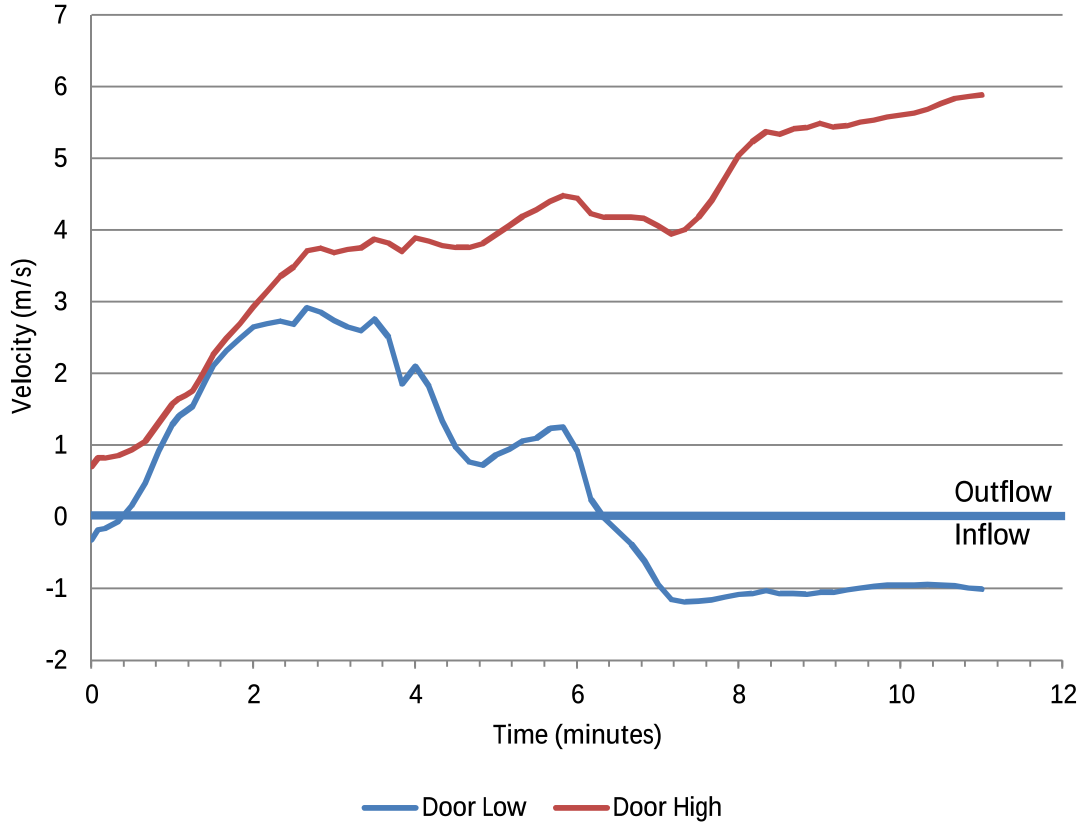


Figure 175 – Velocity at first floor storage area door for Scenario 4

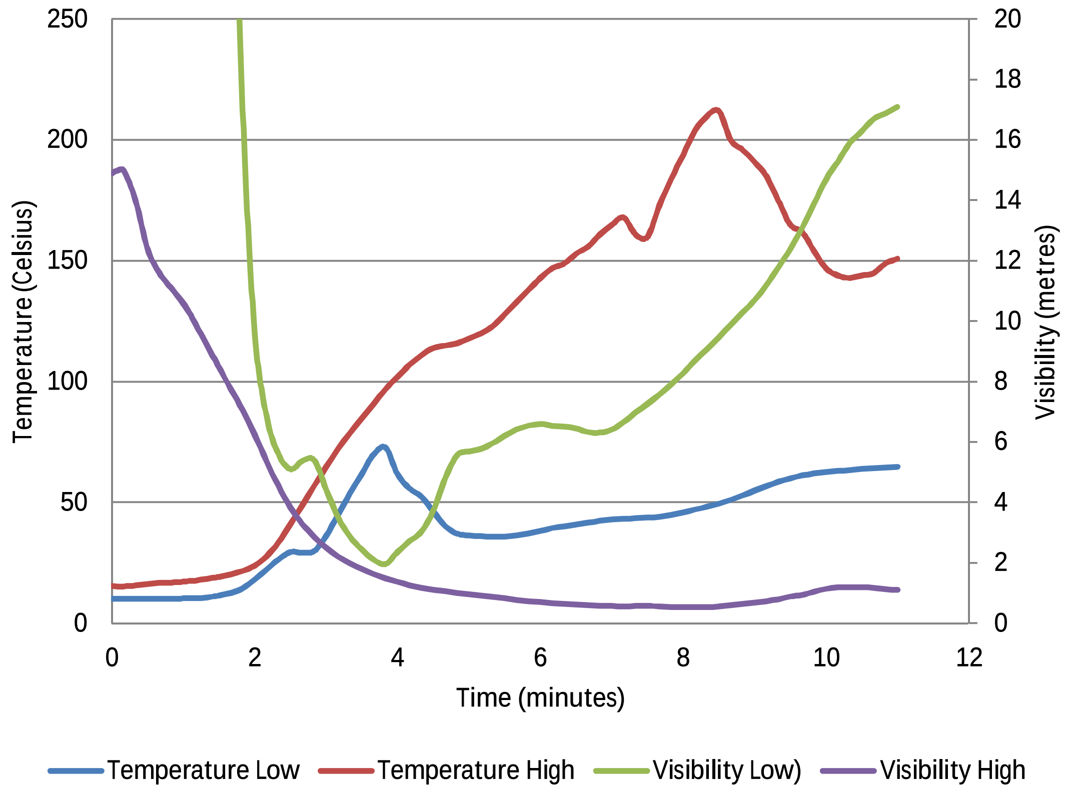


Figure 176 – Temperature and visibility in the lift corridor at location L (shown on Figure 168) for Scenario 4

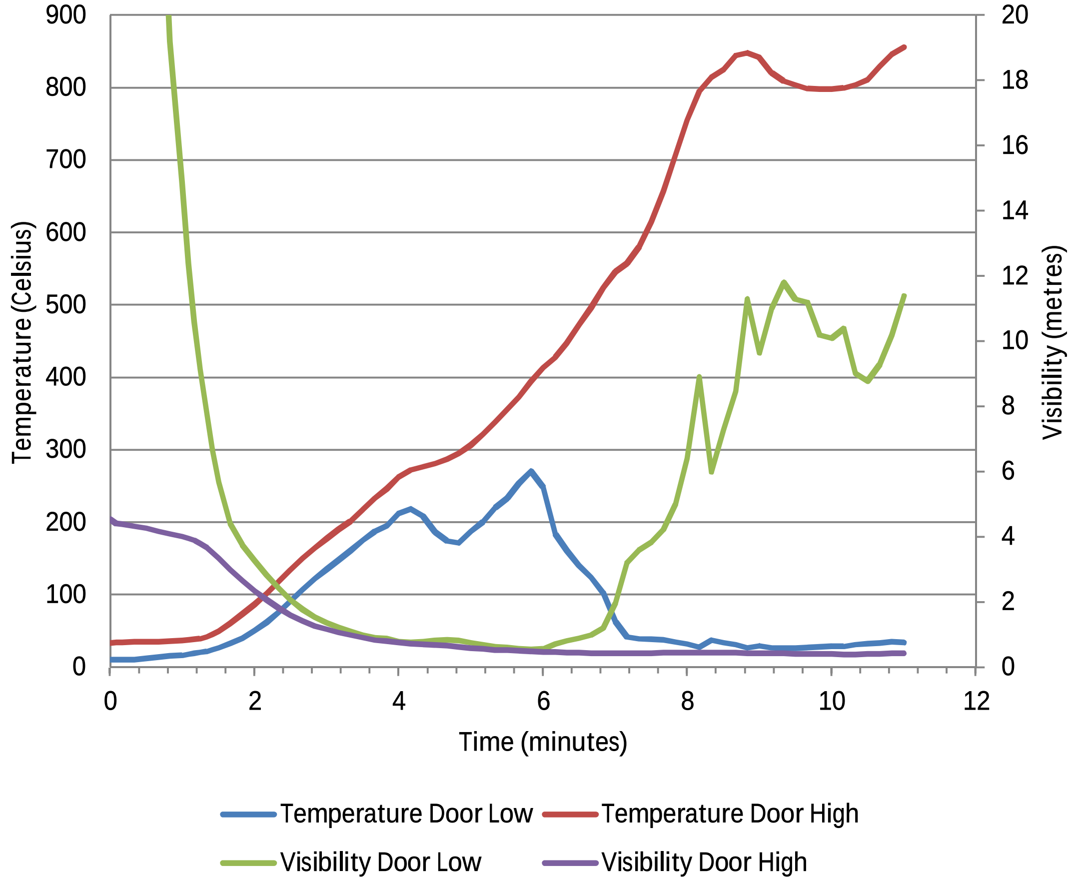


Figure 177 – Temperature and visibility at opening in four hour wall for Scenario 4

3.2.4.8. Number of Secondary Pallets

Scenario 4 assumed all eight of the pallets surrounding the primary pallet ignited due to the primary pallet collapsing; this occurred when the total heat release rate in the redundant stock bay area was 4.6MW. If fewer pallets ignited, ignition of the tertiary pallets could also be expected to occur when the total heat release rate reached 4.6MW as this would create similar temperature conditions in the area. Following the assumption of an ultra fast heat release rate for the fire growth of the secondary pallets, Table 29 gives the time after collapse for the tertiary pallets to ignite.

Number of pallets	Time from collapse of primary pallet to ignition of first tertiary pallet (seconds)
3	90
4	80
5	70
6	64
7	60
8	55

Table 29 – Ignition time for different numbers of secondary pallets

Note that the simultaneous burning of at least three secondary pallets would be required to start the rapid fire growth predicted by Simulation 4.

3.2.4.9. Summary of Scenario 4

From observations of Reconstructions 1 and 2, the principal mechanism of fire spread from the pallet first ignited was by burning material from a collapse of the pallet reaching a second pallet. When the temperature in the area containing the pallets reached a critical value, further pallets could be ignited by thermal radiation and pilot ignition from the burning brands. Simulation 4 indicated this would occur in the redundant stock bay when the total heat release rate reached 4.6 MW. This corresponds to at least three secondary pallets burning simultaneously 90 seconds after the collapse or all eight surrounding pallets burning after approximately 1 minute. As the fire in the redundant stock bay grows, the floor becomes involved and the fire spreads into the first floor storage area.

The fire then propagates through the first floor storage area consuming all of the oxygen available within the volume. The temperature in the first floor storage area remains high as there are very small heat losses through the walls due to their high insulating properties.

Figure 171 shows that after the ignition of the secondary pallets the temperature at location A, near the door to the first floor storage area, rises at a steady rate of about 100ºC per minute.

The simulation assumes that the integrity of the first floor storage area is maintained. However during the actual incident some of the panels may have become displaced due to the high temperature and over-pressure; this would allow more oxygen to enter the space increasing the heat release rate, but also allowing some of the heat to escape from the otherwise highly insulated space.

3.2.4.10. Scenario 5 – Effect of Alternative Ventilation Openings

One variation was simulated here, which was to assess the effect of ventilation openings on the west elevation, one opposite the entrance to the first floor store and one in the bay adjacent to the redundant stock bay. Compared with Simulation 3, the conditions at head height were very similar. However, conditions at low level were slightly improved.

3.2.5. Incident Timeline – Work to Supplement Computer Modelling

The incident that occurred at Wealmoor Atherstone was considered as a number of distinct phases of fire growth. The findings from the reconstructions indicated that there was an extended period of relatively moderate burning at a steady rate of heat release. In Reconstruction 2, this period was followed by a sudden increase in fire size. During this period of sudden increase in fire size, the fire growth rate approximately followed the Ultra Fast fire growth curve as defined by PD 7974 Part 1[149].

Following analysis of the timeline it became apparent that Scenarios 3 and 4 of the computer modelling cover two very distinct sets of fire development. The sequence of events provided in the incident timeline contains observations which indicate that there may be a another Scenario; ‘Scenario 3a’, that needs to be considered where fire development is occurring at a rate that is greater than that dealt with in Scenario 3 but less than the runaway fire spread that is seen in Scenario 4.

Simple calculations were therefore completed to investigate the feasibility of such an interim scenario occurring, whereby temperature increases might be sufficient to account for the observations recorded in the timeline, but where these temperature increases are not sufficient to lead to runaway fire spread.

Given the scenario being considered, these calculations must necessarily assume that heating occurred relatively homogenously throughout the volume of the first floor storage area; at no time did any localised temperature reach a value sufficient to cause runaway fire growth and spread (note that this assumes a level of mixing and therefore homogeneity of the smoke layer that is unrealistically high for this building). The calculations were therefore carried out assuming that the temperature of all of the air and steel remain uniform as it is heated. These calculations also assume no heat losses from the system being heated; note that the highly insulated nature of the building means that heat losses would have been minimal until the fire broke through the building envelope.

The internal dimensions of the first floor storage area were taken as being as follows:

Width: 60m

Depth: 28.8m

Height: 3.2m.

It was assumed that any difference in the overall volume of air due to the presence of stock and partitions was insignificant. It was also assumed that the contents of the first floor storage area had no effect on the heating of the air. The overall volume of air was therefore 5529.6m^3. The density of air was taken as remaining constant at 1.1 kg/m^3. The mass of air, M_{air}, was therefore 6083kg. The specific heat capacity of air, $c_{p\ air}$, was taken as remaining constant at 1.04 J/kg.K.

It was assumed that the surface of the volume of air within the first floor storage area was in contact with a layer of steel 2mm thick. This steel was assumed to occupy the outer walls and ceiling of the first floor storage area plus both sides of three partition walls running the 60m width of the compartment. It was assumed that the floor had no effect on the heating of the air and steel. The overall volume of steel was 6.897m^3. The density of steel was taken as remaining constant at 7850 kg/m^3. The total mass of steel, M_{steel}, was therefore 54139kg. The specific heat capacity of steel, $c_{p\ steel}$, was taken as remaining constant at 0.46 J/kg.K.

Each burning pallet was assumed to have a constant heat release rate, Q, of 300kW. Given these parameters and assuming a constant rate of heat release, the temperature change, T, at any time after ignition, t, in seconds, can be calculated using the following formula:

$$T = t\left(\frac{Q}{(c_p.M)_{air}+(c_p.M)_{steel}}\right) \tag{15}$$

Using this equation the temperature rises for between 1 and 4 burning pallets can be calculated at 1 and 2 hours following ignition. Cells highlighted in red indicate that the temperature exceeds the threshold layer temperature for flashover indicated by the computer modelling (i.e. 400°C).

Calculations were carried out to examine the effect of varying the amount of steel that was heated during this process as well as varying the amount of air (through inclusion/exclusion of a hot smoke layer halfway up the height of the compartment and inclusion/exclusion of the air in the lift lobby being heated.

The dimensions of the lift lobby were:

Width: 38.9m

Depth: 11.3m

Height: 3.2m.

The overall volume of air in the lift lobby was therefore 5529.6m^3 and the mass of air in the lift lobby was 7360kg.

Fire duration		1 hour				2 hours			
Percentage of steel heated		100%	75%	50%	25%	100%	75%	50%	25%
Fire size	300kW (1 pallet)	35	43	58	86	69	86	115	172
	600kW (2 pallets)	69	86	115	172	138	173	230	344
	900kW (3 pallets)	104	130	173	258	207	259	345	516
	1200kW (4 pallets)	138	173	230	344	277	346	460	688

Table 30 – Temperature increases occurring within the first floor storage area for a homogenous air/smoke layer

Fire duration		1 hour				2 hours			
Percentage of steel heated		100%	75%	50%	25%	100%	75%	50%	25%
Fire size	300kW (1 pallet)	38	49	69	115	77	99	138	230
	600kW (2 pallets)	77	99	138	230	154	198	277	460
	900kW (3 pallets)	115	148	207	345	230	297	415	690
	1200kW (4 pallets)	154	198	277	460	307	396	553	920

Table 31 – Temperature increases occurring within the first floor storage area for a hot smoke layer occupying 50% of the height of the space

If it is assumed that mixing occurs throughout the air in the lift lobby as well as the air in the first floor storage area, then the temperatures achieved are as follows:

Fire duration		1 hour				2 hours			
Percentage of steel heated		100%	75%	50%	25%	100%	75%	50%	25%
Fire size	300kW (1 pallet)	33	41	53	76	66	81	106	153
	600kW (2 pallets)	66	81	106	153	132	162	212	305
	900kW (3 pallets)	99	122	159	229	197	243	318	458
	1200kW (4 pallets)	132	162	212	305	263	325	424	610

Table 32 – Temperature increases occurring within the first floor storage area and lift lobby for a homogenous air/smoke layer

Fire duration		1 hour				2 hours			
Percentage of steel heated		100%	75%	50%	25%	100%	75%	50%	25%
Fire size	300kW (1 pallet)	37	48	66	106	75	95	132	212
	600kW (2 pallets)	75	95	132	212	150	191	263	424
	900kW (3 pallets)	112	143	197	318	224	286	395	636
	1200kW (4 pallets)	150	191	263	424	299	382	526	848

Table 33 – Temperature increases occurring within the first floor storage area and lift lobby for a hot smoke layer occupying 50% of the height of the space

These calculations indicate that the temperature rise occurring from a limited number of burning pallets could feasibly raise the temperature of the first floor storage area and lift lobby to the threshold temperature for flashover over a 2 hour period.

3.2.6. Incident Timeline based on Fire Incident Data, Reconstruction and Modelling

The programme of work undertaken identified the following to be key points that were significant in the way in which the incident on 2nd November 2007 developed.

From ignition (sometime prior to 17:20), the fire developed on the first pallet, activating smoke detectors and the fire alarm at approximately 17:20.

Sometime between 17:24 and 17:35 attempts were made by the building occupants to extinguish the fire using hand held extinguishers. These attempts are understood to have subdued the fire for a short while, but did not extinguish it. After the attempt at extinguishment, the fire re-established itself and continued to burn on the first pallet for some time. At some unknown times between this time and 18:42, additional pallets became involved.

WFRS arrived at the scene at approximately 17:52. At this time it is understood that there were no external signs of smoke or fire. Given that the building was a refrigerated warehouse and therefore well sealed, and given the amount of smoke visible on the footage taken by the BBC over two hours later, this appears entirely plausible.

By 18:04, the fire had produced sufficient smoke to reduce the visibility in the lift lobby down to no more than 1 metre (entry 21 of the incident timeline includes ‘not being able to see his hand in front of his face’). At this time, the temperatures in the lift lobby and first floor storage area were not significantly elevated. However there was sufficient heat uniformly distributed throughout the height of the first floor storage area to prevent any useful operation of a thermal imaging camera there.

Sometime during the following 24 minutes, it becomes apparent that there had been a significant temperature rise in parts of the first floor storage area. Attempts at gas cooling indicated elevated temperatures as water was being vaporised. Throughout this period there appears to have been a gradual temperature rise within the compartment, although conditions within the first floor corridor and reception area indicate that the smoke production (and air consumption) was not exceeding the capacity of the first floor storage area.

At approximately 18:49, it is no longer clear whether temperature increases were occurring gradually or whether the fire involved a sufficient number of additional pallets to be approaching, or to have passed, its critical threshold for runaway fire spread. Sometime between 18:49 and 19:15, the critical threshold was passed and the fire rapidly escalated, resulting in temperatures exceeding 600°C throughout the majority of the first floor storage area within six minutes.

It is understood from the WFRS timeline that the fire fighting team designated ‘Red 1’ entered the first floor storage area shortly after 18:53.

3.2.7. **Sequence of Events Relevant to Analysis**

The critical events in the Atherstone fire were the surpassing of a critical smoke temperature/downward radiant heat flux around the area where the fire started (sufficient to ignite and rapidly spread fire across the surface of chipboard floor) coinciding with the entrance of a crew of fire fighters into the large, smoke filled compartment, at the far end of which was the fire.

The rapid development of the fire reduced the visibility down to less than a metre and increased temperatures. The increase in temperatures had the initial effect of softening fixings holding cables against the ceiling, so that these dropped down and may have entangled the fire fighters. The temperature went on the increase to a level well beyond that which was tenable. The data from the modelling which is most likely to represent the conditions to which the fire fighters were exposed are shown in Figure 178.

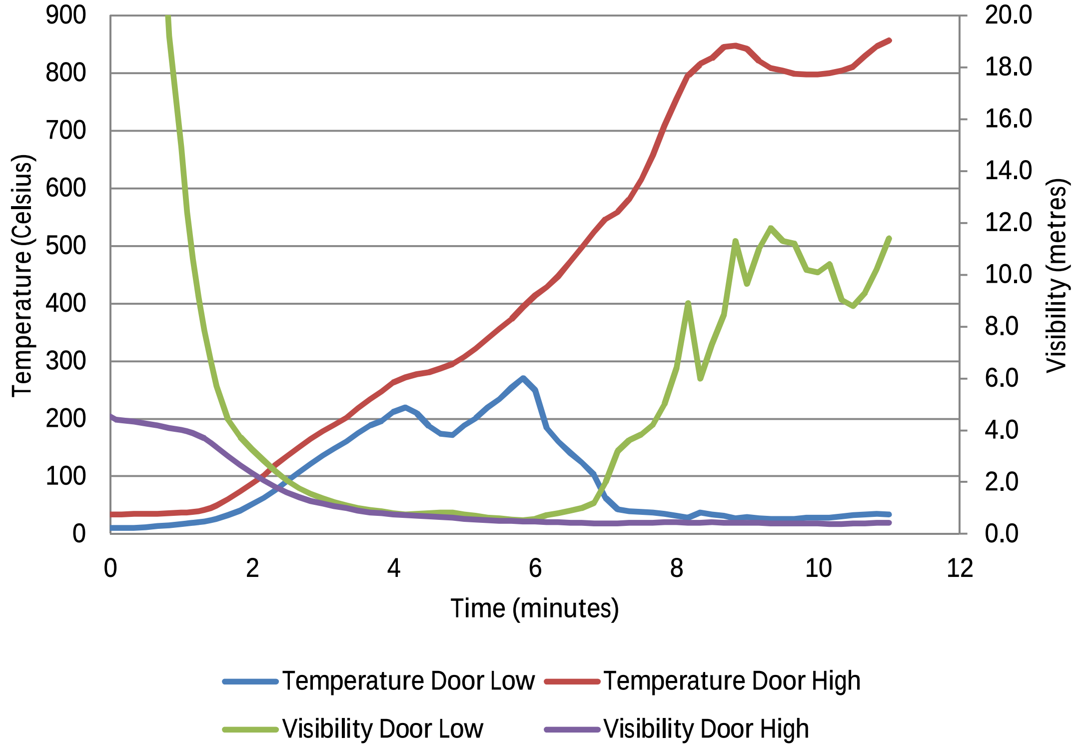


Figure 178 – Data used from Atherstone modelling data for FED calculations. Time zero represents the time at which runaway fire spread started

3.2.8. **FED Data from Experimental Data**

Given the techniques fire fighters are taught to search and wayfind in environments with little or no visibility, the models for hazard analysis proposed in ISO 13571 cannot be considered relevant as it is intended for and built around the capabilities of civilians to deal with restricted visibility environments. The analysis has therefore been limited to that of the effect of heat on the fire fighters. The significance of the FED curve shown at Figure 179 is similar to the curves for Harrow Court (Figure 46 and Figure 48); the sudden increase in hazard in both incidents has obvious implications for fire fighters in those situations. It is interesting to note that the increase in hazard is less marked for Atherstone than it was for Harrow Court; this would tend to indicate that there was a longer timeframe available for fire fighters to effect escape in Atherstone than there was in Harrow Court. However, the size and complexity of the layout of Atherstone in relation to Harrow Court would more than account for the additional time available as it would be required for fire fighters to exit the relevant compartment.

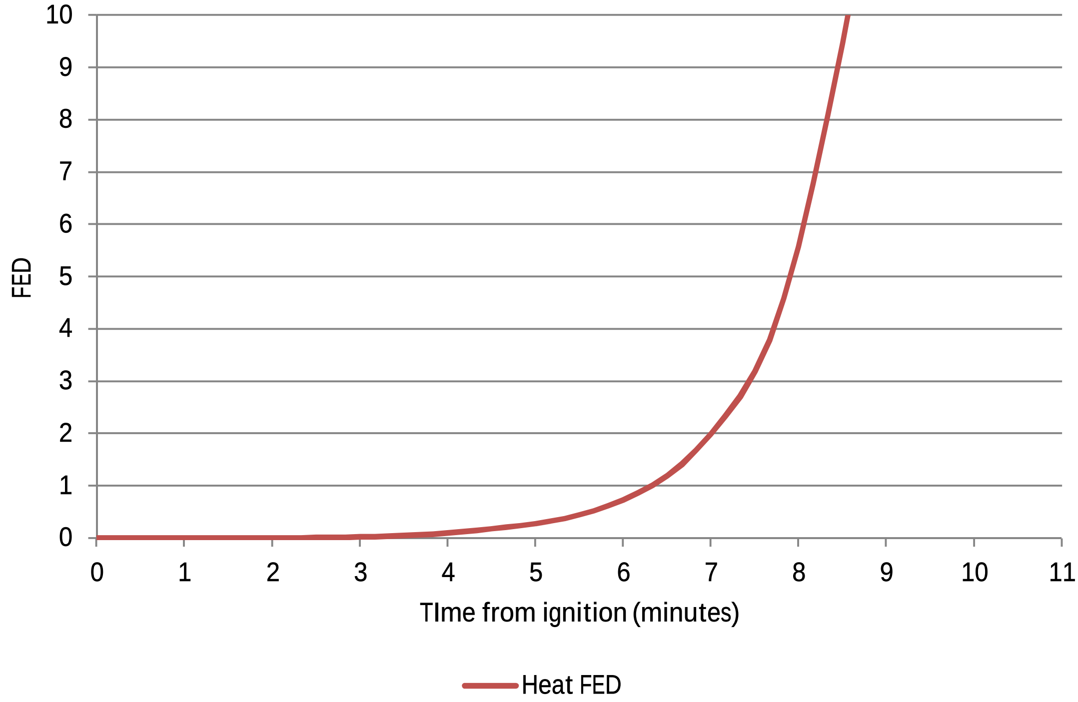


Figure 179 – FED values calculated using ISO 13571 method based upon Atherstone modelling data. Time zero represents the time at which runaway fire spread started

4. DISCUSSION

4.1. Stardust Disco

It can be seen from the experimental data in chapter 2.1 and the FED data, that the reconstruction fire does not appear to have provided an accurate representation of the initial period of the fire where it remained small for some ten minutes or so. The repeated attempts needed to ignite the reconstruction highlight the uncertainty involved in replicating fire conditions and it seems probable that the final successful attempt produced an ignition scenario more severe than the actual incident and consequently bypassed the initial period. Time zero on the FED data below might therefore be considered to correlate with the start of the period of rapid fire growth at 01:42 during the incident.

Applying 01:42 as time zero on the FED plots allows significant events to be marked onto the FED plots so that the information concerning movements of people (although vague) can inform the relationship between severity of conditions increasing during the incident and the cause of death of the victims, see Figure 180 and Figure 181. Both of these FED plots have also been shaded where the $CO:CO_2$ ratio exceeds 0.1, indicating under-ventilated conditions at the annex point (i.e. near the fire to eliminate secondary combustion effects at the vent). Note that arrival of the fire brigade was at 01:51, so falls outside the time period covered by the FED plot (i.e. fatal conditions were reached prior to their arrival).

As mentioned in chapter 2.1, whilst the locations of the victims of this fire were recorded, it is not known which victim was which and therefore which postmortem blood analyses are relevant to each victim. However, it can be seen from Figure 6 in chapter 2.1 that relatively few victims died from smoke inhalation alone. This is supported by the FED plots for the annex (near the fire origin) and vent (away from the fire) points, which show that the hazard posed by toxic gases reduced significantly away from the fire during the evacuation period, whereas there was a high hazard presented by heat in either location. This indicates that hazard from heat was high regardless of victim location, whereas only those victims which remained close to the fire would have been significantly affected by smoke and toxicity.

The materials involved in the Stardust fire and the findings from the tribunal provide some indication of the reason why this pattern of fire hazard arose. It is known that carpet tiles were fixed to the walls of the room and these were shown to contribute significantly to the development of the fire, along with the fuel presented by the seating on which the fire started. The seats in the Stardust disco are known to have comprised polyurethane foam covered in PVC, which clearly would have contributed to the quantities of hydrogen cyanide and hydrogen chloride produced during the fire.

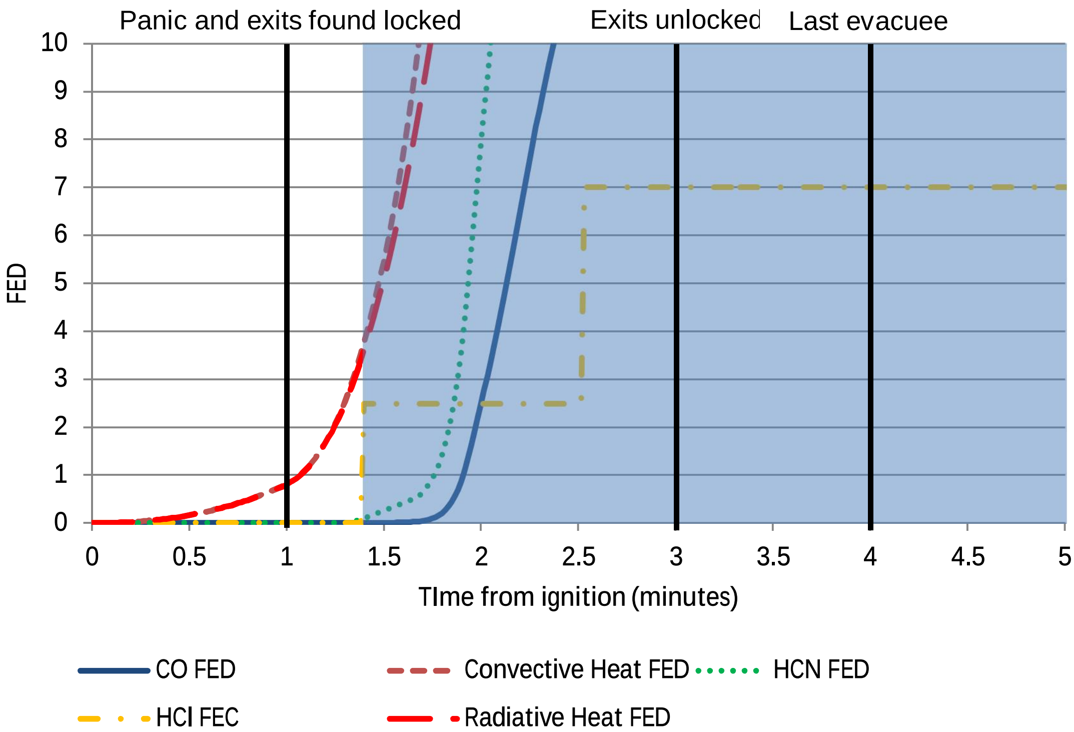


Figure 180 – FED values based upon Stardust reconstruction annex point measurements. Markers have been added to show relevant events. The shaded area indicates where under-ventilated conditions are predicted by CO:CO_2 ratio exceeding 0.1

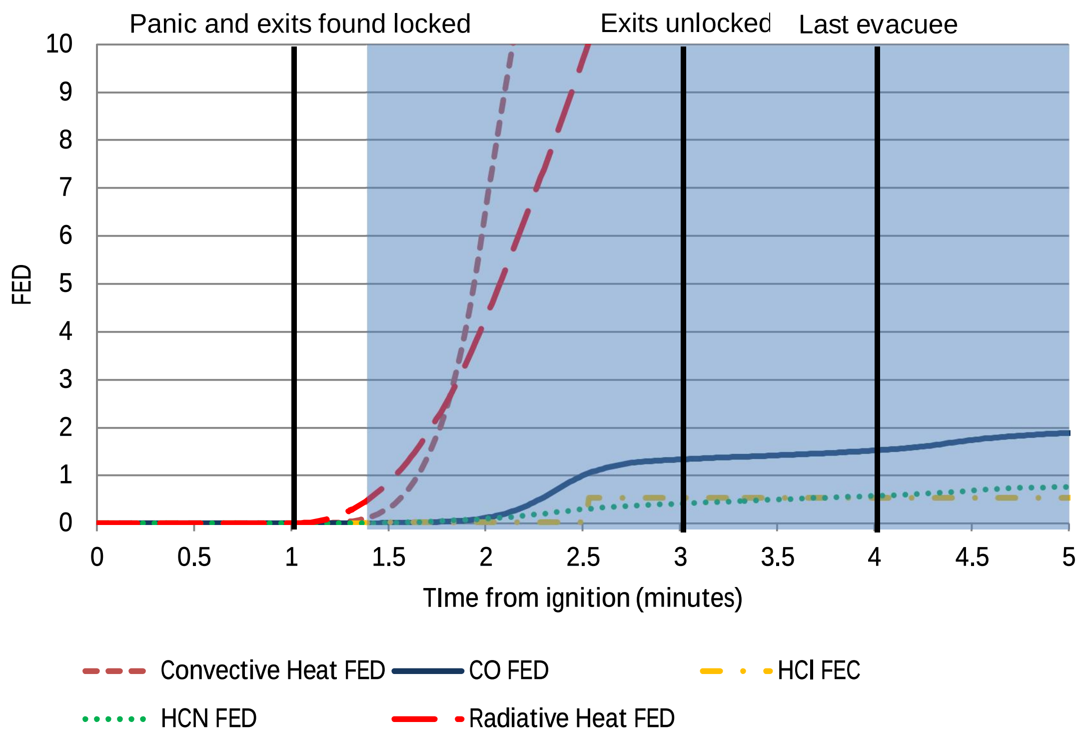


Figure 181 – FED values based upon Stardust reconstruction vent point measurements. Markers have been added to show relevant events. The shaded area indicates where under-ventilated conditions are predicted by $CO:CO_2$ ratio exceeding 0.1 on Figure 180

It therefore appears that the key factors in the Stardust Disco fire were the materials used to line the walls, ceiling and seating contributing to the rapid growth of the fire, and the locking of the exit routes by security personnel, reducing the number of means of escape from the premises. The fire was able to develop and grow extremely quickly as a result of the various fuels that were available for it to do so and the amount of air in the large compartment to support it. Severity of conditions, both heat and concentrations of combustion products, increased rapidly as the fire developed.

As no information is available concerning either the locations or the movements of specific victims during the incident, it is not possible to make any detailed analysis concerning their whereabouts and corresponding cause of death, although it is likely there would have been a mixture of responses, with some people ignoring the fire, others initially moving towards it out of curiosity and some immediately moving towards an exit. Given that heat became the dominant hazard in this fire; it is likely that once fire development started to rapidly increase, panic would have caused a rush for the exits, resulting in the crush conditions reported in the Tribunal of Inquiry, although the evidence indicates that no one died as a direct result of crush injuries.

4.2. Maysfield Leisure Centre

The reconstruction of the fire at Maysfield Leisure Centre provided data which appears consistent with the information from the incident, although as with Stardust the incident data is somewhat vague; in this instance accurate to the nearest five minutes. It is therefore difficult to estimate the time during the incident which correlates with time zero on the reconstruction but given that the fire was discovered at 13:35 and there was no sign of fire at 13:30, an ignition time somewhere between the two seems plausible. Evacuation of the building is reported to have started sometime between 13:35 and 13:40, with the fire brigade arriving at the scene at 13:40 and casualties starting to be brought out at 13:45. Therefore the entire period from ignition, through discovery/evacuation and fatal conditions being achieved took less than 15 minutes. This is supported by the FED plot which shows conditions changing from "safe" to fatal in a matter of seconds, largely driven by the contribution of hydrogen cyanide to the overall toxicity in the space, see Figure 182.

All of the victims were in locations are/or moved through spaces which brought them in contact with smoke in or spilling out of the main corridor (see Figure 19 in chapter 2.2). Given the dramatic change in severity of conditions once under-ventilated conditions were achieved and large concentrations of hydrogen cyanide (and carbon monoxide) started to be produced, it is perhaps unsurprising that victims were overcome by the smoke before they were able to leave the building. It is unfortunate that there was an extended postmortem interval prior to samples being taken for hydrogen cyanide. It seems likely that the impact of hydrogen cyanide may have been underplayed at the time due to the decreased measured levels and the lack of knowledge concerning the importance of postmortem interval on detection of hydrogen cyanide. The photographs from the reconstruction and witness evidence from the survivors of the fire also indicate that the thick, dark smoke produced by this fire would have significantly hampered movement through the building, although no quantitative data is available to assess this.

Significant quantities of polyurethane foam and rubber crumb contributed to the production of hydrogen cyanide during this fire. The recommendations arising from this fire recognised the importance of smoke toxicity but dealt with it indirectly; via the general management/control of fire and methods to keep smoke away from people, rather than making any recommendation which might lead to a change in the combustion products being formed, as was the case across the developments in fire safety at the time (see chapter 1.3.2).

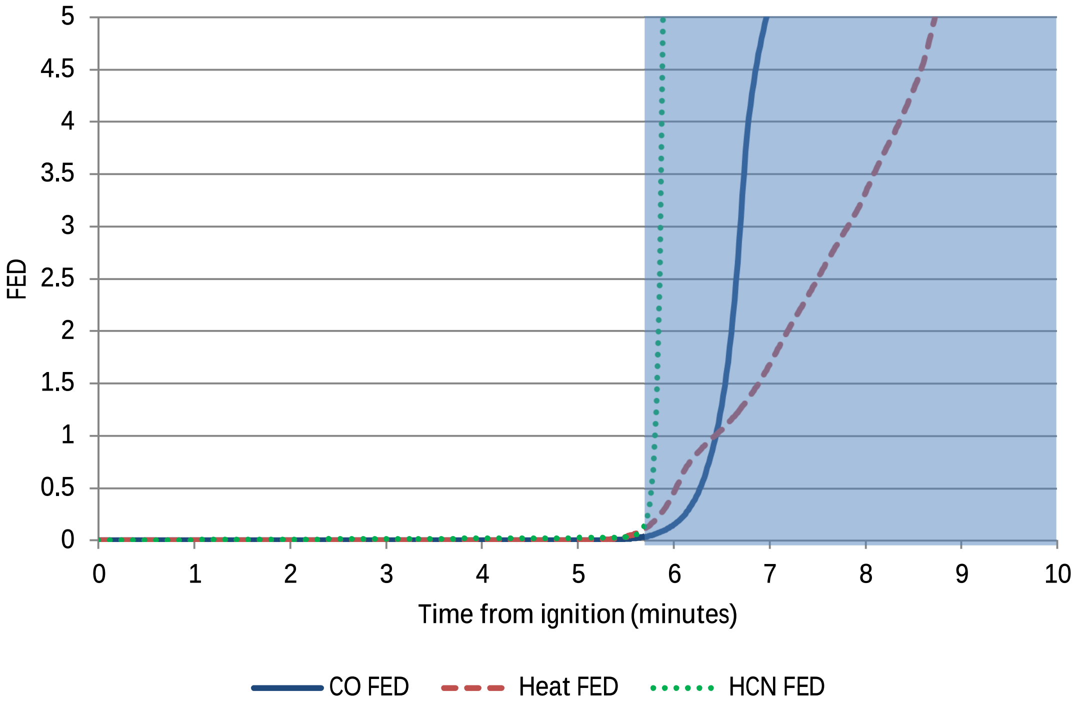


Figure 182 – FED values based upon Maysfield reconstruction data. The shaded area indicates where under-ventilated conditions are predicted by $CO:CO_2$ ratio exceeding 0.1

The key factors in the fire at the Maysfield Leisure Centre were the materials involved in the fire and the doors in the building (in particular the door to the store room) being left open by the occupants, allowing the products of combustion to be dispersed throughout the building and air to get into the fire, so that it could continue to grow.

The fire was able to grow to flashover, at which point the toxicity of the environment, in terms of both asphyxiant gases and heat, increased considerably. The ultimate cause of death of all of the casualties of this fire was the inhalation of toxic gases and smoke. The FED analysis highlighted the significance of hydrogen cyanide in this incident, which once examined more closely (particularly with regards to postmortem interval before blood analysis) highlights the importance of identifying hydrogen cyanide at as early a stage as possible during an investigation.

The progression of the fire was reported as difficult to understand at the time of the reconstruction, but current knowledge indicates that this fire developed entirely as we would now expect; as energy feedback increased as the fire grew to involve the entire room, fuel pyrolysis increased and the fuel:air ratio increased, so the fire condition became ventilation controlled and large quantities of products of incomplete combustion were produced and introduced into the atmosphere in the building. Given that polyurethane foam and rubber crumb made up a significant proportion of the fuel load, it is also now entirely understandable that large quantities of hydrogen cyanide were produced by this fire and that this was the primary contributor to the overall hazard in the environment.

4.3. Rosepark Care Home

The reconstruction of the Rosepark Care Home fire indicated that a variety of different conditions were created throughout the different areas of the building. The mobility impairment on the part of the residents meant that there was no opportunity for them to self-evacuate and so they were reliant upon the fire protection measures that were in place.

The fatal accident inquiry found that the fire was most likely to have started at 04:28. Work carried out by Purser as part of the fatal accident inquiry (correlating toxic concentrations in blood with those measured in the reconstruction) found that time zero of the reconstruction correlated with 04:30, due to the incident having been started by an electrical fault whereas the reconstruction was initiated using two number 7 cribs[47].

Of the fourteen victims of the Rosepark Care Home, ten were in rooms off of corridor 4 with their doors open. All of these people died at the scene. It can be seen from Figure 183 that the delays caused in finding (and therefore confirming) the fire and calling the fire brigade meant that there was little opportunity for rescue of any of these residents prior to them being overcome by the effects of toxic gases in the area. Note that actuation of the fire alarm in the incident occurred approximately 90 seconds before time zero of the reconstruction. There was therefore over 7 minutes available following actuation of the fire alarm when evacuation of the residents could have taken place, of which 3 minutes might have been with the assistance of the fire brigade.

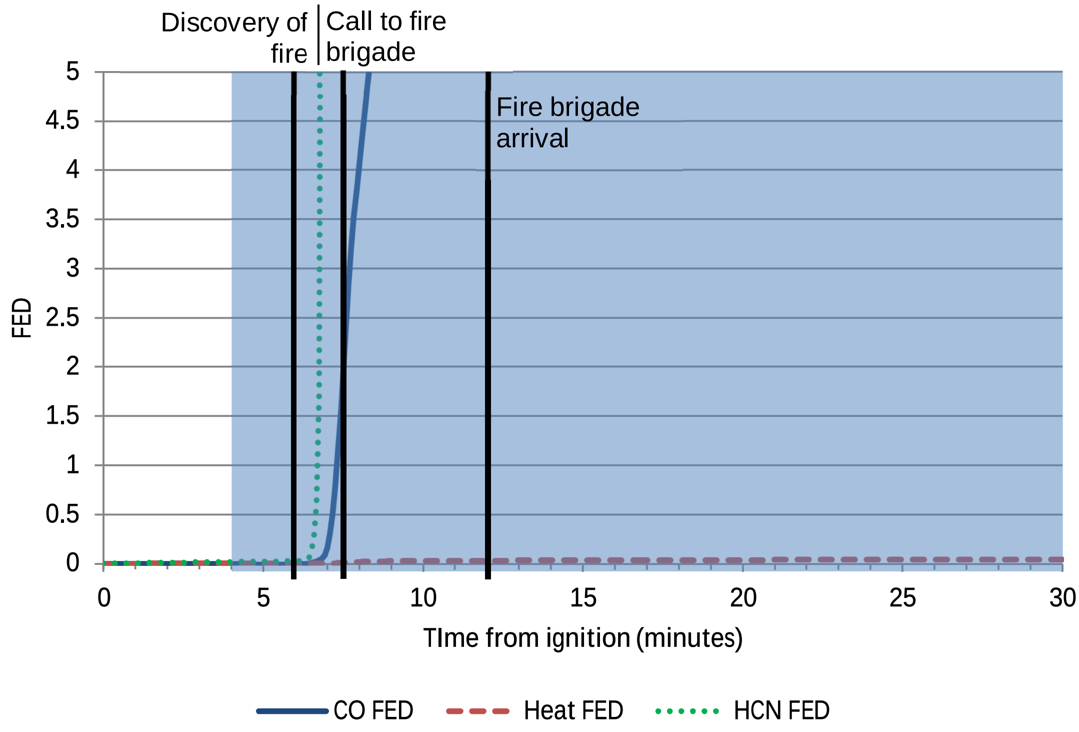


Figure 183 – FED values calculated using ISO 13571 method based upon Rosepark open room reconstruction data. Markers have been added to show relevant events. The shaded area indicates where under-ventilated conditions are predicted by CO:CO_2 ratio exceeding 0.1

The other four victims of the fire were all in rooms which were separated from the origin of the fire by at least one closed door. It has been hypothesised that one of the major contributing factors towards their deaths (all of which occurred in hospital, after having been removed from the building) was taking them from the relative protection of the room they were in and carrying them through the smoke filled corridor.

Deceased	Corridor	Door	COHB measure-ment/ estimate*	Time removed from room	Time from ignition (0428)
Female, room 10	4	Closed	43-49	0540	72 minutes
Female, room 18	3	Open	44-53	0611	103 minutes
Female, room 20	3	Open	42-55	0600	92 minutes
Female, room 11	4	Closed	43-57	0509	41 minutes

Table 34 – Summary of data of residents rescued from Rosepark Care Home fire that died later

Assessing the overall dose exposure of a person passing through different environments is difficult, but a simplification of the problem can be made by simply using the toxic concentrations relevant at the various stages of the incident (i.e. effectively “stitching together” different periods of exposure in different locations/conditions). This has been done in the cases of the victims in rooms 10, 11 and 20; it was not possible for the victim from room 18 as no data existed representing later than 103 minutes after ignition, so this victim can only be considered in relation to corridor 3.

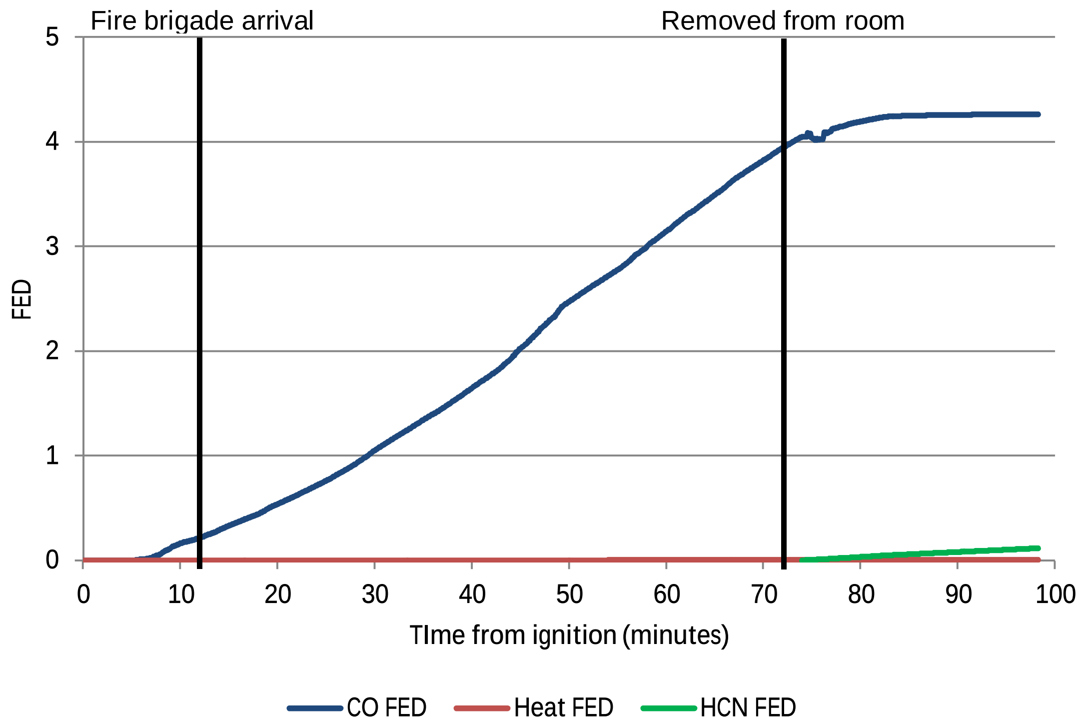


Figure 184 – FED values calculated for Rosepark room 10 casualty. Markers have been added to show relevant events

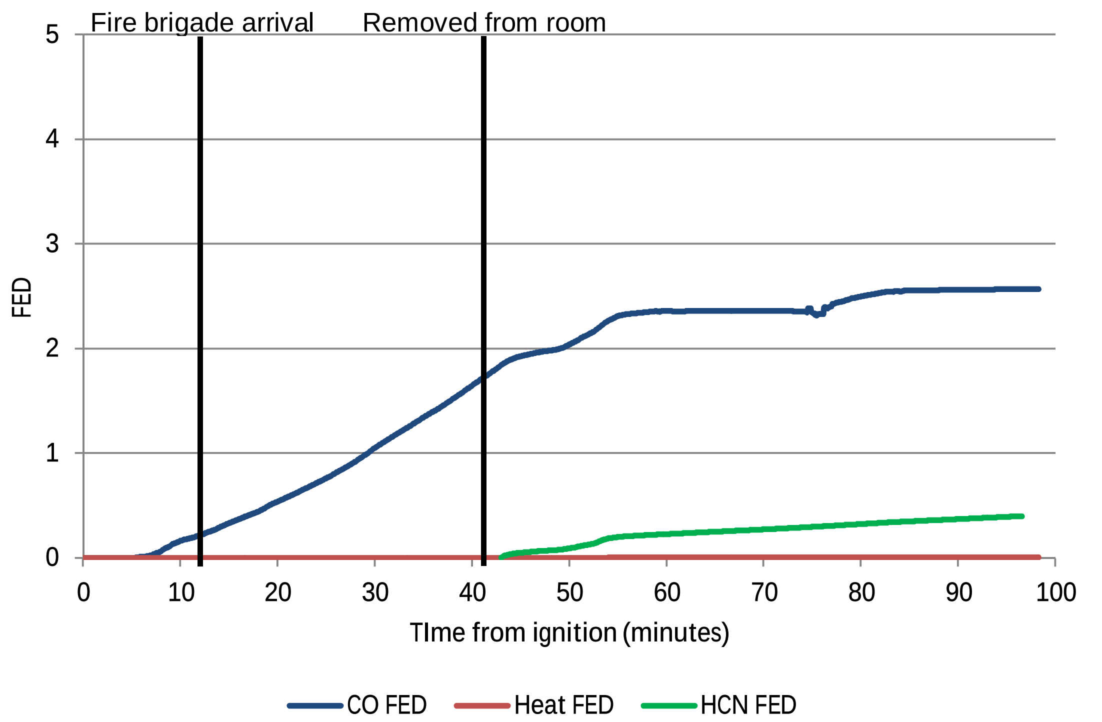


Figure 185 – FED values calculated for Rosepark room 11 casualty. Markers have been added to show relevant events

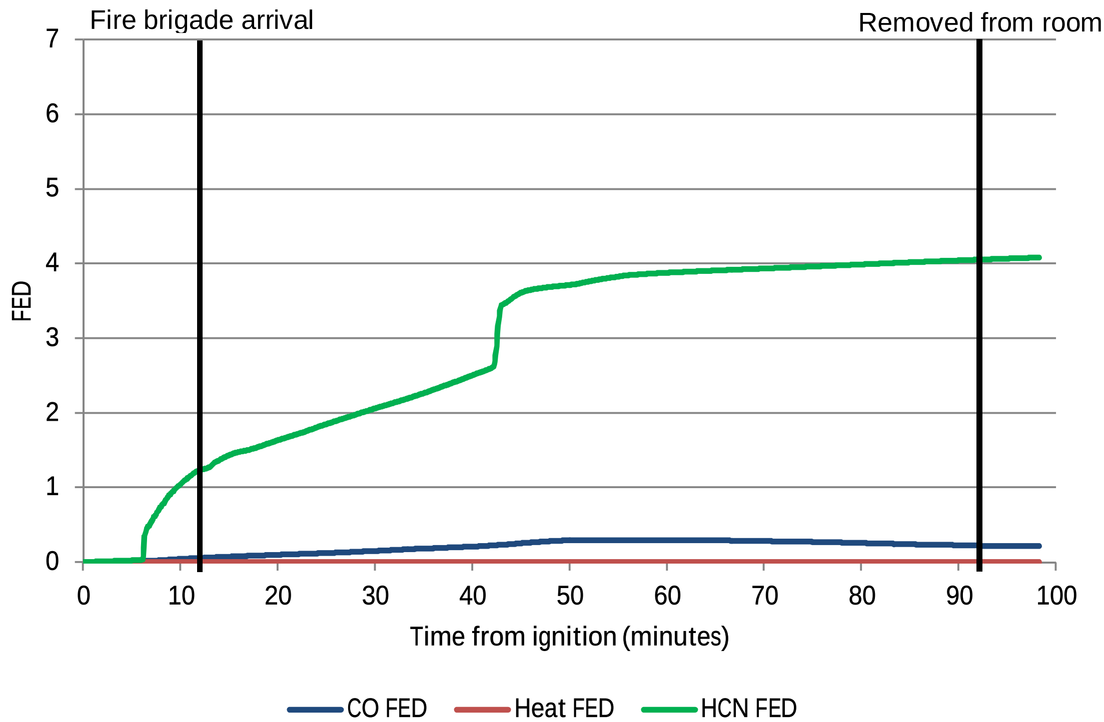


Figure 186 – FED values calculated for Rosepark room 20 casualty. Markers have been added to show relevant events

Once this analysis has been carried out, accumulating FED across the route travelled by the victims, it can be seen that the dose they received following their move is actually much less significant than the dose received prior to that time. However it is possible that this additional exposure, although minor, might have been sufficient to cause the death later on, particularly if it involved exposure to acid gases not measured as part of the reconstruction.

It is interesting to note that the FED calculation for the victim from room 20 does not correlate with her COHb figure (42-55%). The possibility of chronic obstructive airways disease may have contributed but this does not account for the disparity between the reconstruction and postmortem figures.

Unfortunately no measurements were made of the exposure of victims to hydrogen cyanide. This would probably have indicated various levels of exposure to cyanide as the results of the FED calculations from the reconstruction indicate that hydrogen cyanide played a significant role in the overall toxic hazard in the environment.

The analysis indicates that the key factors in the Rosepark Care Home fire were the doors in the building (bedroom doors) being left open by the occupants and the extended period of time for which the victims were left exposed to the products of combustion. The fire did not grow considerably; it was largely contained within the cupboard where it started and self-extinguished due to lack of air within a few minutes. The temperatures during the incident did not get significantly elevated, particularly at locations remote from the fire, but the products of incomplete combustion rapidly dispersed throughout the space.

Of the victims, those that were in rooms which were open onto the corridor where the fire started were rapidly overcome by the severity of the conditions produced by the fire. Those who died later all had one door separating them from the fire corridor. It appears likely that they received a significant proportion of their toxic dose during the period when efforts were being made to effect their rescue.

The majority of the materials involved in this fire were materials that are not controlled by any aspect of Statutory fire safety. However, given that the fire was contained by the design of the cupboard/corridor and that the doors that were open should have been closed (in accordance with Statutory guidance) then it would appear that some increased level of safety might have been achieved if all of the then current Statutory guidance had been followed.

4.4. Harrow Court

The reconstruction of the fire at Harrow Court indicated a fire occurred which underwent a dramatic change in burning conditions (flashover) with a concurrent dramatic increase in the severity of the conditions to which both the civilians and fire fighters involved in the incident were exposed. It is not known what time the fire actually started during the incident, it was seen by a neighbour who called the Fire and Rescue Service at 02:59. It is known that fire fighters reached the flat at 03:04 and that flashover in the flat occurred at 03:08; approximately four minutes later. Assuming that the reconstruction was an accurate representation of the fire, time zero would correspond with approximately 02:38 during the incident. Markers have therefore been added to Figure 187 and Figure 188 based upon that assumption.

It is not known what time the survivor from the flat awoke and went to fetch water to attempt to extinguish the fire. It is highly likely that this occurred prior to the sudden increase in hazard arising from carbon monoxide but that this sudden increase had occurred by the time he returned to the fire, particularly as he reported significantly elevated temperatures at this time.

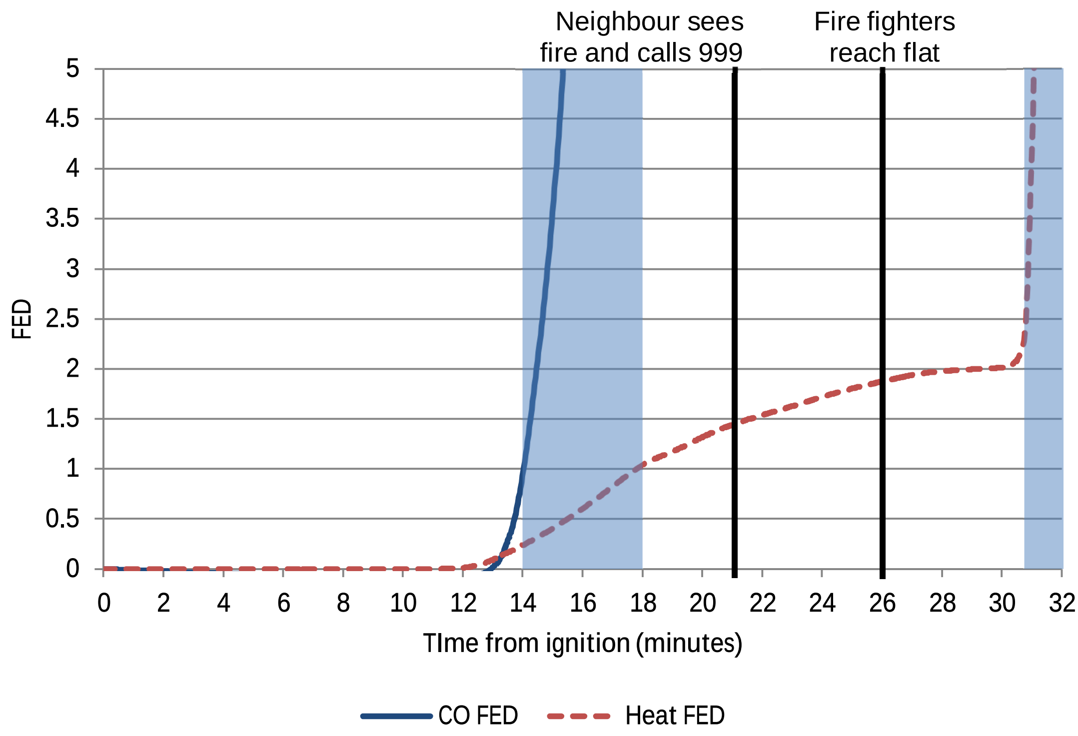


Figure 187 – FED values calculated using ISO 13571 method based upon Harrow Court reconstruction data standing up measurements. Markers have been added to show relevant events. Shading indicates under-ventilated conditions ($CO:CO_2$>0.1)

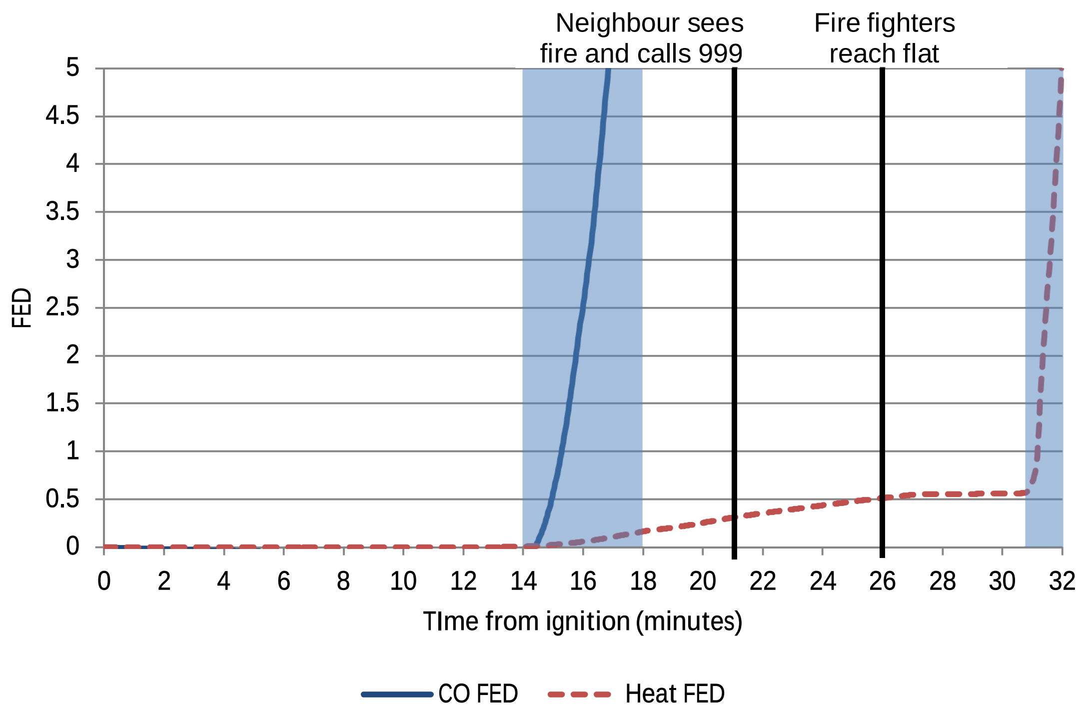


Figure 188 – FED values calculated using ISO 13571 method based upon Harrow Court reconstruction data lying down measurements. Markers have been added to show relevant events. Shading indicates under-ventilated conditions ($CO:CO_2$>0.1)

It can be seen from the FED plots that the female resident (female 2) would have been very quickly overcome by the carbon monoxide concentrations in the room. The conclusion from the inquest that she died as a result of inhalation of smoke presumably indicates that she had an elevated COHb concentration in her blood and probably that there were signs of soot in her lungs as well, although this information is not available for confirmation.

As previously discussed, fire fighters are, by virtue of their breathing apparatus, protected from the effects of toxic gases so are only vulnerable to the effects of heat (provided they do not run out of air). The hazard arising from carbon monoxide, hydrogen cyanide and other inhalable gases is therefore not relevant to fire fighters. They are also afforded some additional protection from the effects of heat by their tunics. However, whilst the level of protection provided by fire fighter tunics is assessed using standard tests, the data obtained from these tests is not useable for FED hazard calculations. It has therefore been assumed that the method prescribed in ISO 13571 for fully clothed individuals is applicable to fire fighters.

The FED plots indicate a dramatic increase in the hazard arising from heat some two and a half minutes after fire fighters reached the flat. Notwithstanding the significant additional risk of fire fighters not having adequate water supplies (the dry rising outlet was locked) and becoming entangled in cables, the sudden increase to an FED of 5 at high and low level in less than a minute is more than sufficient to account for conditions capable of overcoming fire fighters.

The key factors in the Harrow Court fire were the doors in the flat being left open, prevailing wind conditions affecting development of the fire, fire fighting crews not having water available to fire fight at the fire flat, and the crews becoming trapped in cables falling from their surface mounted position on the ceiling of the corridors where fire fighters were working.

The fire grew as a typical compartment fire until it ventilated due to the heat breaking the windows in the flat. The prevailing wind conditions and opening of doors into the lobbies and ventilated central stairwell then rapidly forced the fire into those spaces. The effects of the rapid fire development that ensued were compounded by the absence of any working fire fighting media for the fire fighters in the lobby and their also becoming trapped in the space by cables that had fallen from their fixings against the underside of the ceiling.

4.5. Lakanal

The reconstruction fire carried out in relation to Lakanal provided some data in relation to the conditions which led to the death of the person in Flat 79. However, the limitations on the design of the reconstruction rig meant that conditions predicted in the upper floor of Flat 79 are probably more severe than those to which the victim in Flat 79 was exposed. As previously discussed, the victim in this area survived until a time corresponding with 24 minutes from ignition and is known to have died from a combination of burns and smoke inhalation. It is known that she was sheltering on the floor near a door to the outside and so it is likely that fresh air was entering the area through this point. This would have diluted the fire gases and had some effect on the temperatures in the space.

The FED plot shown in Figure 189 is therefore not representative of the severity of conditions but the general trend of the gradient of the lines is indicative of the times when changes in fire conditions changed the rate at which the FED dose was increasing. Notably, the involvement of the staircase in the flat gave rise to a more steep increase in the FED dose which corresponds with the time of death of the victim.

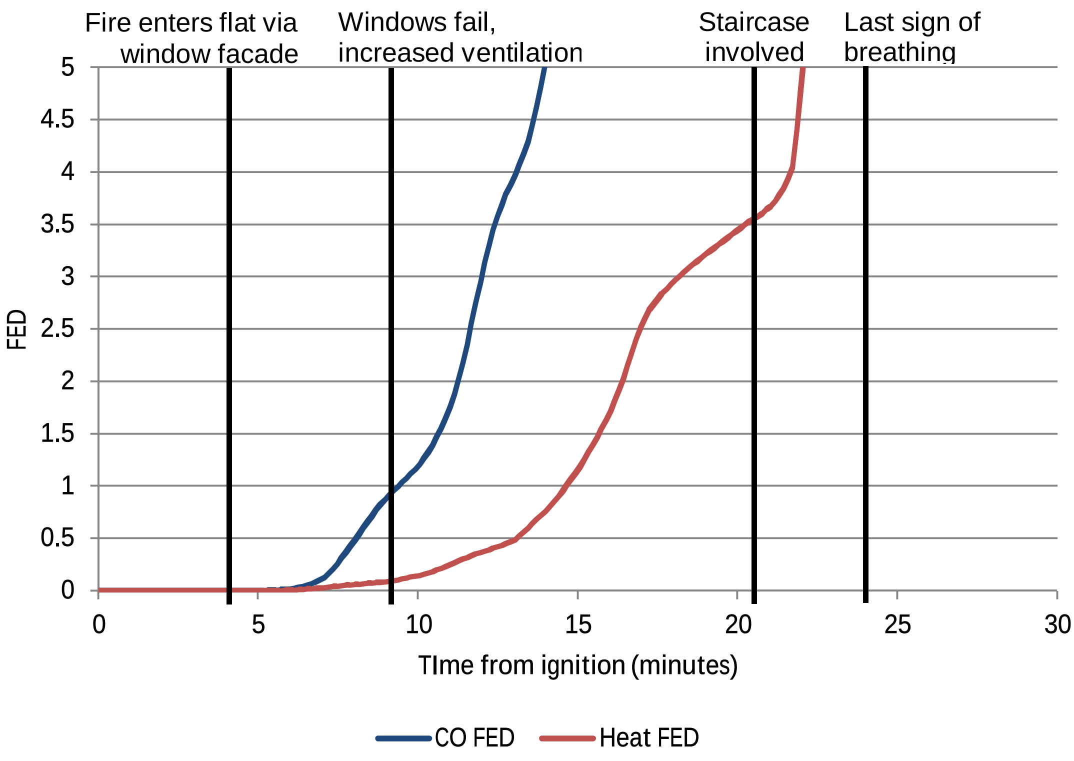


Figure 189 – FED values calculated using ISO 13571 method based upon Lakanal reconstruction data relevant to the fatality in Flat 79

The conditions in the bathroom of Flat 81 of Lakanal could not directly be examined through the use of a reconstruction so it was necessary to rely upon computer modelling and engineering calculations to produce predictions of the rate at which the hazard to life increased in that room. The limitations of the tools used to make these predictions means it was only possible to consider carbon monoxide. In addition, the prediction of CO concentrations and consequent FED in the bathroom of Flat 81 was reliant upon a number of separate processes being accurately "modelled", either via computer modelling or engineering calculations.

However, it is interesting to note that the time at which FED exceeds 1 (102 minutes or at 17:57 during the incident), correlates very well with the times of death returned by the pathologist during the inquest, which all fell between 17:45 and 18:05.[141]

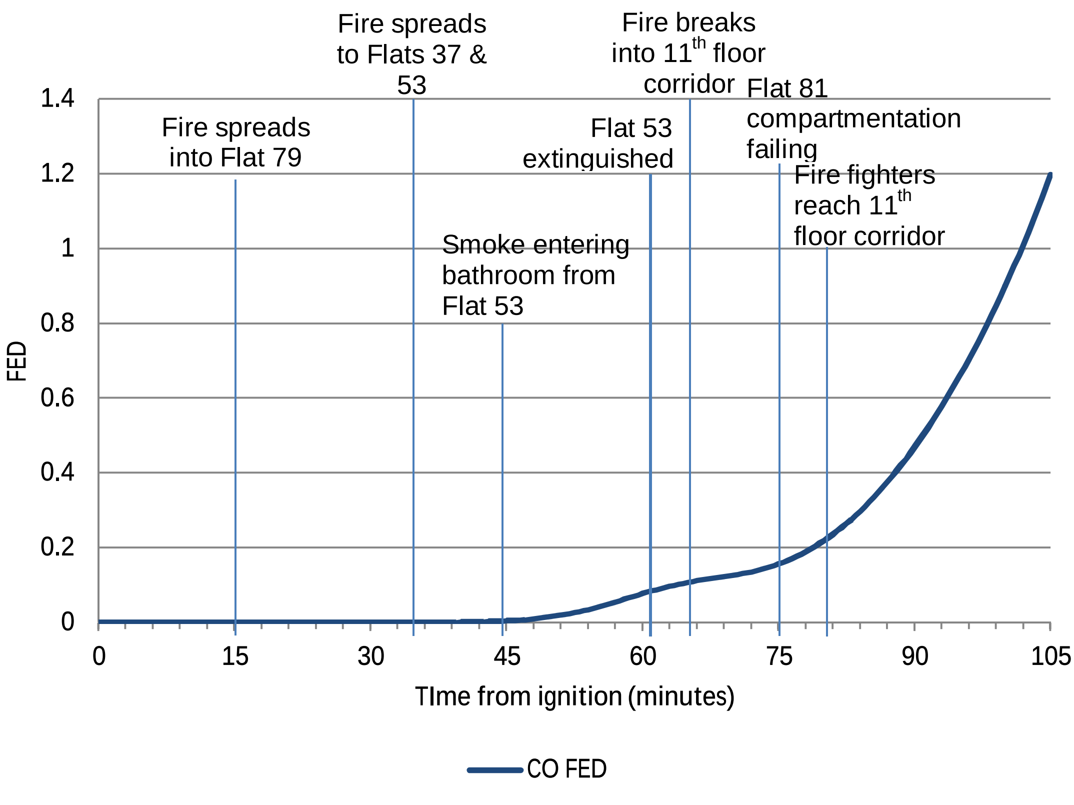


Figure 190 – FED values calculated using ISO 13571 method based upon reconstruction, modelling data and engineering calculations for the bathroom of Flat 81

The sheer number of factors that were involved in this incident cannot be overstated. In addition to the issues of what fuels were present and the way in which the fire was able to develop within the flats, there were also the following factors:

- Surface spread of flame properties of
    - the external envelope of the building
    - the wall and ceiling surfaces of the common corridors
- Standards of fire compartmentation
    - between flats and external escape balconies
    - between flats and the common corridor
        - no smoke seals around fire doors
        - poor fire stopping
        - poorly designed/built ad hoc compartmentation
- No sub-division of concealed cavities
- Compromised ventilation systems
    - cross ventilation allowing smoke movement throughout common areas
    - bathroom extraction system altered by residents, allowing some spread between flats
- The effect of prevailing wind on
    - flame impingement up the outside of the building
    - air movements within the building (interlinked with the cross ventilation)
- Layouts of flats being altered by the residents

Given the number of “things going wrong” on the day of this incident to produce the specific sequence of events, it seems unreasonable to think that anyone could reasonably have predicted this particular outcome. Whilst further improvements to the fire performance of materials, both in terms of flammability and toxicity, could have helped the situation, it would probably be far more effective to simply ensure that the pre-existing fire safety arrangements had been suitably maintained.

4.6. Atherstone-on-Stour

Given the size of Wealmoor Atherstone, it was not possible to directly assess the severity of conditions encountered by the fire fighters through the use of a reconstruction. Reconstruction data had to be combined with the use of test data and computer modelling in order to obtain estimates of conditions throughout a building of this size.

The programme of work indicated that, at some point between 89 and 115 minutes into the incident, a sudden change in the development of the fire resulted in rapid increase in temperatures throughout the very large fire compartment. The FED plot for the area where the four fire fighter victims are understood to have been when they were overcome is shown in Figure 191.

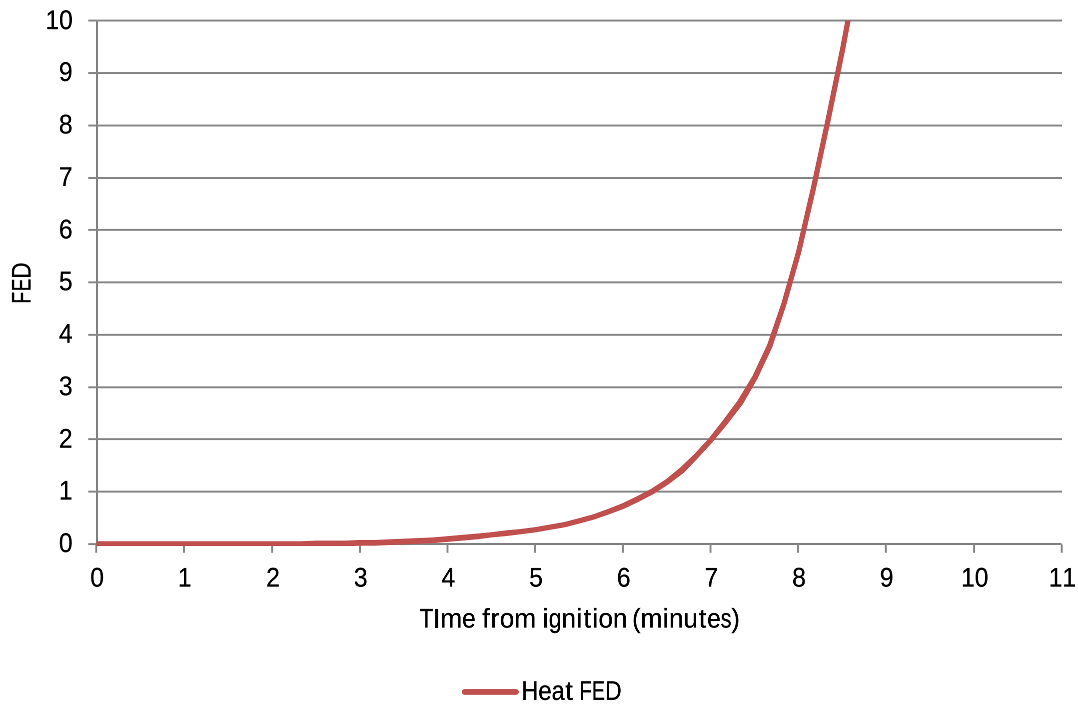


Figure 191 – FED values calculated using ISO 13571 method based upon Atherstone modelling data. Time zero represents the time at which runaway fire spread started

The rapid escalation of FED value combined with the size of the compartment and the knowledge that fire fighters may have become entangled in cables and/or disoriented within the large compartment, provides ample explanation of the way in which the rapid escalation could have resulted in their deaths. However, the FED plot may be further adapted using the work investigating the gradual increase in temperatures throughout the incident and the turnover of crews being exposed to the environment in the compartment.

Assuming a linear growth to the critical temperature of 400°C (determined as the threshold temperature for ignition of all combustible surfaces in that environment), a new temperature profile and corresponding FED curve can be developed. This is shown in Figure 192.

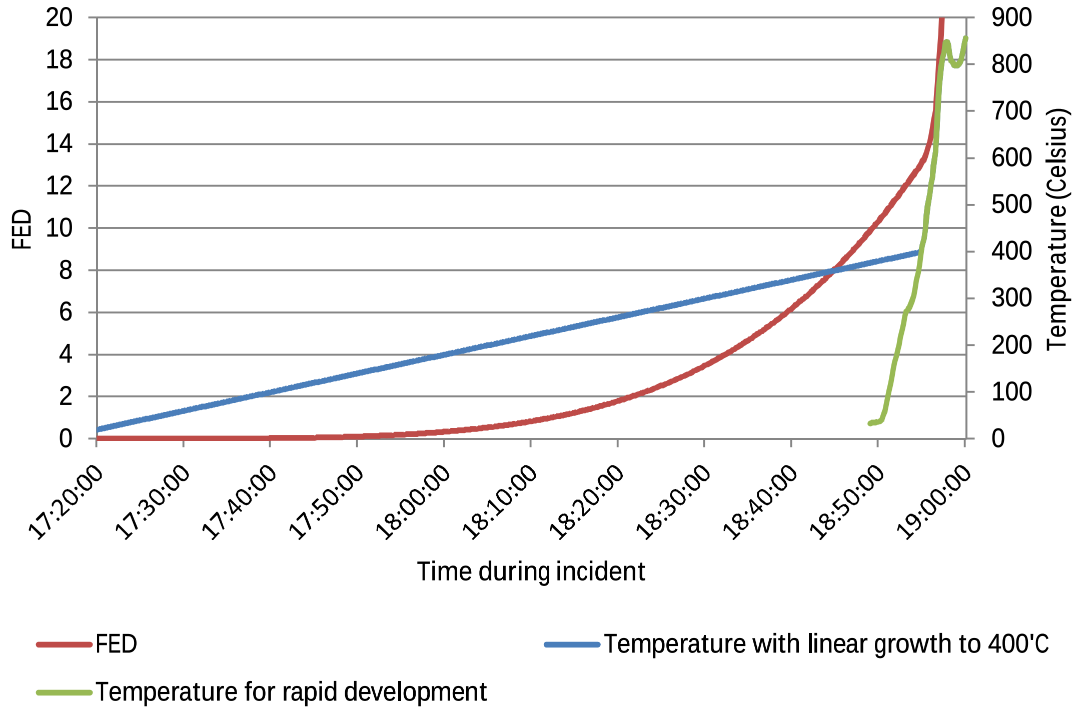


Figure 192 – Temperature profile and corresponding FED values based upon combination of Atherstone modelling data and linear growth

Further analysis of the FED plot for the incident, which takes account of the turnover of crews during the course of the incident, provides some insight into the validity of the ISO 13571 approach for fire fighters. For each crew turnover (a fresh pair or team of fire fighters entering then leaving the space) the FED is reset to zero so accumulation of FED only occurs during the period of exposure, as shown in Figure 193.

This analysis indicates that fire fighters are, perhaps unsurprisingly, able to withstand temperatures well above those of fully clothed civilians. The highest ISO 13571 FED value attained by a surviving crew was 5.4, although the time to reach this value (15 minutes) was less than the previous crew; who attained 2.6 over 23 minutes.

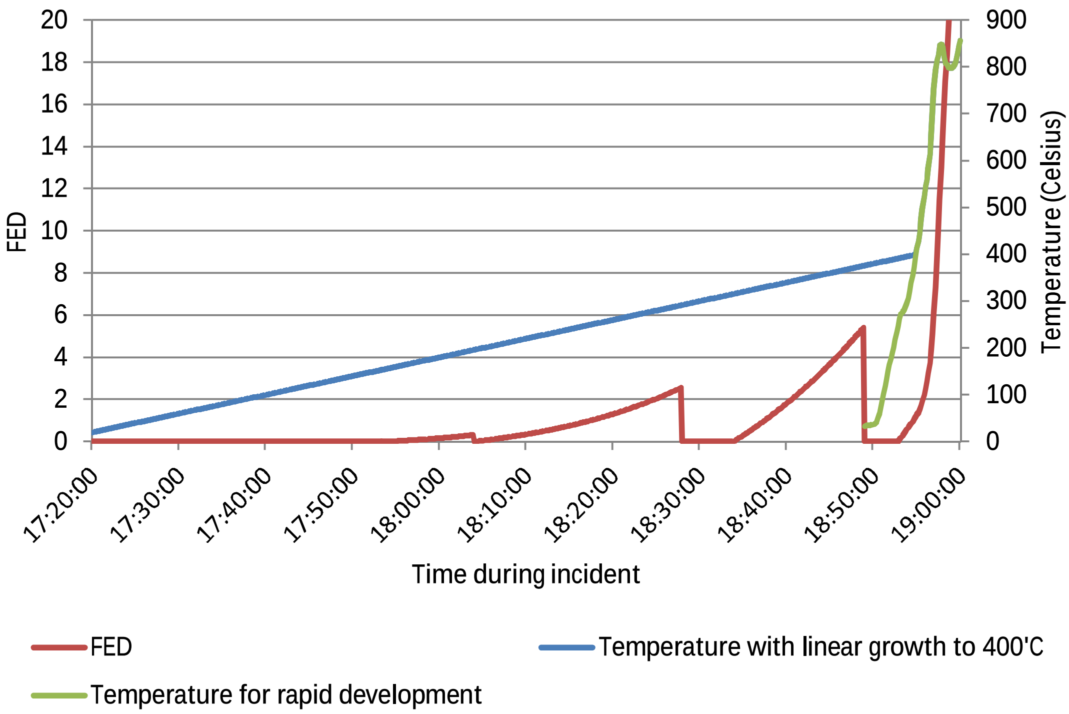


Figure 193 – Temperature profile and corresponding FED values based upon combination of Atherstone modelling data and linear growth, with resetting of FED in line with crew turnovers

The fire at Atherstone-on-Stour can be considered simply as a fire developing in a very large, highly insulated compartment. The issue that necessitated the programme of work that was carried out was the timing of the speed of development of the fire, in particular the time at which sudden fire development occurred to involve the entire compartment.

Given that this is the case, and that the work carried out has demonstrated the significant role played by the linings of the compartment (fuel load from floor and insulation by walls and ceiling), it should have been possible for a fire engineering analysis involving the burning behaviour of the floor and the insulation of the compartment to have predicted the scenario which actually occurred.

The ramifications of this fire have yet to be dealt with by the fire sector, although it has already led to the production of a series of operational bulletins for Fire and Rescue Services on fires in large compartments, rapid fire development, fire fighting techniques and entrapment in falling cables.

5. CONCLUSIONS AND FUTURE WORK

The aim of this thesis is to bring together knowledge from fire science with evidence from fire investigation to provide way forward for improving fire safety and protecting life using sound scientific principles. In order to achieve the aim, it was necessary to:

1. Examine the way in which the fields of fire safety, fire investigation have developed into their current form.
2. Consider the knowledge surrounding the fire performance of materials with respect to both flammability and toxicity.
3. Examine and consider the statistics that are available concerning fatal fires. Data was considered at both a national level, using publically available statistics, and at a local level, using data obtained from London Fire Brigade and its real fire library.
4. Investigate the link between fire hazard studied at bench scale level and full-scale fire incidents, to consider how an assessment of hazard (and therefore acceptability of hazard) is currently reached).
5. Investigate the way in which hazard to life escalates during the course of real incidents where multiple fatalities have occurred, so that the contributing factors to these escalations in hazard level could be identified and considered in relation to the assessment of hazard carried out at bench scale.

5.1. Objective 1

The history of fire safety and the way in which it has evolved provides some insight into the reasons behind the modern fire safety framework. Developments in fire safety have been limited by knowledge in fire science, during which time trends in fire deaths and major catastrophes have been the driving force behind decisions to improve upon the fire safety framework. This framework has comprised a number of constituent parts, chiefly controls around the use and management of combustible or flammable materials in day-to-day life, the design and construction of buildings and the provision of emergency response. Establishing and then improving upon this framework in more recent years has necessarily involved a considerable amount of scientific research across industry and academia, but there remains an opportunity to identify trends and related areas of research through the examination of real life incidents. This examination and analysis of real incidents is essential to ensure that research remains relevant to the issues arising in real life.

The development of early fire safety can be summarised as a series of measures and resources put into place in response to a number of tragic events, with the hope of avoiding repetition of those events in future. The measures were initially simple directives; things that should or should not be done in order to avoid future repetition of events, and were generally based upon empirical measurements of fire experiments. The resources (fire scientists) have been accruing knowledge over a number of years and the level of knowledge that is now available concerning the behaviour of fire means we are now starting to understand the physical and chemical processes fully that are responsible for the behaviour heretofore measured empirically.

5.2. Objective 2

The test methods which measure the properties of materials and products to assess their performance have to be appropriate to the level of knowledge that is available to apply the resulting data to the design of a building. Given the wide range of design complexity that exists and will continue to exist throughout the world, there is and will always be a need for a range of test methods and data which can cater for the range of design approaches which may be applied to any building. As such, there will always be a need for test methods that can distil the properties of a material or product down to a pass/fail or a classification.

Much of the debate concerning modern test methods centres on the issue of how well one or another test represents actual burning conditions. The advantage of carrying out full-scale reconstructions of incidents is that this issue is negated (although there remains an issue of accuracy). Given the importance of the larger environment in determining what conditions a fuel will ultimately burn under and the consequent hazard to which relevant individuals will become exposed, it seems clear that there is a need for these two divergent approaches to be brought back together so that a truly holistic estimate of hazard to life can be carried out.

5.3. Objective 3

The ever decreasing number of fire deaths per year is an outstanding achievement for the fire sector at large, but it has led to an ever diminishing evidence base on which to make decisions about future improvements to the framework. In particular, recent advances in the knowledge surrounding the physical and chemical processes governing fire are well understood by academia and mirrored by the remaining evidence base reported by the fire investigation forum, but low numbers of fire deaths means is a lack of impetus for change with those responsible for the fire safety framework. This poses a challenge for those who wish to continue to push for developments and improvements, but must nonetheless be recognised as a considerable success for the work that has already gone on in the past.

The statistics which have, until recently, been collected across the UK indicate that the principal contributing factors to deaths in fires are exposure to heat/flame and exposure to smoke/inhalation of toxic gases, although there have been changes in the relative proportions of these factors over time, with exposure to smoke generally increasing in significance relative to other factors. However, this coarse data indicating general cause of death does not provide any information that could be considered useful in terms of identifying the root cause of death. More detailed statistics which were collected at a national level nearly 50 years ago provided a level of detail which allowed assessment of, among other things, which materials/products contributed to the cause of death and the locations of fatalities relative to the origin of the fire. This level of detail allowed analysis to take place which contributed to developments such as the modern Building Regulations and the Furniture and Furnishings Regulations, both of which have been extremely successful in reducing fire deaths, but is a level of detail which is no longer available today at national level. It might be considered that the cessation of collection of this level of detail was due to the success of these previous measures and the consequent reduced priority which fire safety has been afforded. Fortunately, there remains some data collection at this level, albeit only at a local level. Of the data that was obtained, it supports the pattern of historic data that points towards the importance of fires involving furniture and the relative significance of heat/burns in fatalities close to the origin of the fire, versus the importance of smoke/toxicity in fatalities some distance away from the origin of the fire.

5.4. Objective 4

In all of the incidents analysed, the follow-up reviews at the time considered means by which the tragic sequences of events might have been mitigated. Maysfield Leisure Centre and Stardust Disco both gave rise to consideration being given to material performance:

- Maysfield through the performance of foam filled furniture and the Furniture and Furnishings Regulations, which were introduced 4 years later.
- Stardust through the performance of surface linings, although it should be noted that in this case the surface spread of flame properties of the linings fell well short of the standard already expected at the time.

The Rosepark Care Home and Harrow Court fires both led to consideration being given to active fire safety measures and to the actions of the Fire and Rescue Service to be taken in such incidents.

- The Rosepark reconstruction was immediately followed by a repeat experiment where the reconstruction rig was fitted with a sprinkler system. Following the success of the system in mitigating the severity of the conditions, sprinklers became a mandatory feature for all new care homes in Scotland. The actions of the Fire and Rescue Service were reviewed, particularly with regards to familiarisation visits to high risk premises such as care homes in the hope that this would improve times to rescue in future incidents.
- The Harrow Court fire led to a review of both the provision of dry rising mains and associated equipment in high rise blocks of flats, and the standard operating procedures to be adopted by Fire and Rescue Services when attending fires in high rise blocks.

In all of these cases, the number of instances in which the intended actions/measures failed to occur points towards a need to consider whether another method may be more appropriate for ensuring fire safety. The model approach to sustainable development would tend to indicate that rather than trying deal with the consequences of a developing fire by containing or managing heat and smoke, some effort to be directed to towards mitigating the growth of the fire at its source. In the incidents examined, such a measure might have provided a further level of mitigation, allowing people more time to escape or effect rescue. However it must be recognised that these were catastrophic events where numerous fire safety measures failed, leading to catastrophic loss of life.

When significant incidents occur which warrant the carrying out of in depth investigation or even a reconstruction, they provide an opportunity to gather high quality data which can support and complement the data gained from national statistics by providing an opportunity to look into the root causes of fire deaths. The question posed by the multi-fatality incidents that have been examined, particularly those as recent as Lakanal and Atherstone, is whether some improvement in the way in which the fire safety framework is put together could have prevented them.

All of the incidents that have been investigated and analysed as part of this thesis were a culmination of a number of things going wrong all at once. This is now invariably the case in multi-fatality complex fires and is a positive reflection of the way in which fire safety has evolved; it appears as though all of the factors that might be capable of producing such a tragic event in isolation have been dealt with. Equally, the package of measures that are provided to ensure the fire safety of any one building is just that; a package. In the UK, the baseline level of fire safety protection defined by the Approved Documents are intended to provide a package of measures which are capable of protecting life even if one or two of the measures within that package are found wanting.

The incident analyses carried out have shown that an FED risk assessment based approach might have been capable of predicting the fatal outcome of some of these situations. However, the relative foreseeability of these incidents needs also to be considered.

- Maysfield Leisure Centre fire, as a scenario, seems entirely predictable provided that the leaving open of doors is considered to be a realistic possibility. The fuels involved in the fire were specific to that environment (gym materials in a leisure centre) and would now be controlled to some extent under the Furniture and Furnishings Regulations, although non-compliance with such regulations may also need to be considered a realistic possibility.
- Rosepark Care Home fire was the culmination of a large number of things "going wrong" including doors being left open, inaction by staff and confusion regarding the building layout. The Sheriff responsible for the Fatal Accident Inquiry identified 7 reasonable precautions and a further 5 defective systems of work variously responsible for the deaths that occurred. Predicting when and how such a number of deficiencies

might fit together in any one incident seems implausible without running an exceptionally large number of scenarios. Even then, the scenarios would have to be able to consider the possibility of all of these “things going wrong”.

- The speed with which the fire at the Stardust Disco spread was predominantly a product of material properties. The materials involved; surface linings and upholstery on fixed furnishings, are all now controlled under either the Furniture and Furnishings Regulations or the Building Regulations. The way in which these controls are executed should certainly deal with the issue of rapid fire spread from a small fire source, but the interaction of burning properties with production of smoke and toxic gases is only controlled indirectly, and so needs continued consideration in light of more recent incidents.
- The fire at Harrow Court was, at its core, a compartment fire which was able to become fully developed and was then significantly influenced by ventilation conditions. The behaviour of compartment fires is reasonable well understood given that it tends to be governed by limits on ventilation to the compartment. Equally, fire fighting in high-rise blocks of flats is known to be subject to the effects of wind. There is currently no methodology for predicting the effect of wind gusts on the development of a fire but the complexity of this problem, involving prevailing wind direction and speed as well as local air currents around a building, mean this problem is unlikely to be solved any time soon.
- The sheer number of contributing factors that were present in Lakanal cannot be overstated. Even setting aside trying to develop an understanding of the cocktail of toxic species that ultimately contributed to the dose inhaled by each of the six casualties, there was a huge number of factors that contributed to smoke and toxic gas movements. The number of factors present here raises the question of the relative probability of any one of the factors coming into play during any one incident. As such, in identifying the risk to which people might be exposed during the course of any one incident, there needs to be a consideration of the relative probability of the entire range of scenarios that might take place within a building.
- The fire at Atherstone-on-Stour was an extremely complex incident but, at its core was a relatively simple concept; a highly insulated building and a fire in a compartment containing a very large fuel load. As shown during the analysis of the fire, one of the

principal contributors to the overall size of the fire was the chipboard floor. Floors are not currently controlled surfaces under Building Regulations, but the way in which this fire developed raises a question: In the case of highly insulated warehouses, heat from fire is far more contained than in other cases and sudden development may lead to rapid change in conditions some distance away from the seat of the fire. Is control of the floor surface and/or contents therefore necessary where a combined area and insulation criterion is reached? And how best is this control achieved?

5.5. Objective 5

Two aspects of hazard to life have been examined as a result of this work; that arising from exposure to toxic products of combustion and that arising from exposure to heat. Each of these strands has its own particular factors which need to be considered, but both stem from the quantity and type of fuel that is available within an environment and the way in which the fuels burn during the course of an incident. The primary focus of this work has been the contribution of the materials to the overall hazard but as has been seen from the incidents examined the actual burning conditions are necessarily dependent upon the environment (usually building or room) in which the fire takes place. This means that carrying out a full assessment of such a scenario must necessarily involve both;

- the contribution of a material and it is interaction with local burning conditions, and
- the overall conditions generated by the fire taking place within a particular building or environment.

The two points above have for some years been dealt with as separate topics. Initial work stemming from the Great Fire of London and Tooley Street fires was really focussed on what can now been seen as the effects of heat; with the stated focus being that of limiting the extent of fire damage (property protection and fire fighter deaths). The first scientific works (Faraday's candle experiments and the fuel burning appliances work in the Lancet) considered products of combustion (toxicity) and the heat output/burning conditions to be intrinsically linked. However, as developments continued and modern fire safety (involving compartment fire behaviour rather than combustion) began to take shape in the 1950s, there was a divergence of approach, with toxicity becoming the focus of fire chemists, whilst fire engineers and more generalist fire scientists considered smoke to be something which carried a hazard, but was not fully understood or quantified.

When considering the incidents and corresponding fire reconstructions in terms of the areas of flammability and toxicity, a pattern can be seen to emerge with regards to the location of the victims and the relative complexity of the scenario which resulted in their deaths. The victims that were overcome by heat were all, as one might expect, inside or close to the compartment of fire origin. Fire fighters in particular, by virtue of seeking out the seat of the fire so that they can extinguish it, will necessarily put themselves in an environment that is close to either the origin of the fire or an area where it is developing when they suffer injuries. Conversely victims that are overcome solely by the effects of toxic gases have all, in the multi-fatality cases examined, been some distance away from the fire, such that the incident really needs to be considered in terms of both the direct cause of death; the concentrations of smoke to which the victims were exposed during the course of the incident, and the indirect cause of death; the reason/s why the smoke came to be in an area of the building remote from the seat of the fire, and the reason/s why provisions for warning and means of escape had been insufficient to allow the victims to effect an evacuation before the smoke reached their location.

The analysis that has been carried out in all of the incidents proves that there is sufficient knowledge available to understand the processes responsible. However, the level of detail to which the incidents in this thesis have been investigated and analysed far exceeds the level of detail to which the vast majority of building designs will be considered, and it should be noted that each of these incidents only represents one potential sequence of events which a designer may consider when designing a building. The foreseeability of these incidents must therefore be a factor in considering whether changes in approach might have mitigated them.

5.6. Future Work

Given the foregoing conclusions regarding the importance of the wider scenario issues, issues which might be considered suitable for analysis using fire engineering, it appears that further work may be required to try and develop a methodology which incorporates both the existing hazard analysis related to generation of effluent, and some consideration of the way in which effluent may be distributed in a compartment and then spread beyond that compartment to contribute to the toxicity of atmospheres outside of the fire compartment. This will necessarily involve not only consideration of the dilution of toxic gases as they travel away from the area of origin, but consideration of secondary reactions and solution/condensation of reactive toxic effluents, particularly acid irritant gases.

Furthermore, it has been previously stated that multi-fatality incidents tend to be the result of a large number of things "going wrong" all at the same time. Each of these individual things going wrong may be considered to have a particular probability of occurring at any given time in any given time. The probability of multiple factors all occurring at the same time may be the product of those probabilities (unless issues such as general state of repair come into play, making concurrent related issues more likely than would otherwise be the case). When considering incidents in this way, it becomes apparent that there might be an opportunity for probabilistic analysis to take place, considering all the potential scenarios and potential failures that might occur within a building to provide a holistic analysis of the risk to life.

Ultimately, this work has demonstrated the intrinsic link between what have until now been considered as separate subjects of flammability and toxicity. The hazard analysis carried out for the incidents and their reconstructions has shown instances where heat has been the primary hazard and others where toxicity has been the primary hazard. In either case, the outcome in terms of which hazard takes primacy has been set by the combination of materials involved and the specific circumstances (ventilation conditions and temperature) of the fire. Ultimately, the hazard arising from both heat and toxicity can be considered a product of these core inputs, and are linked as such. The link between flammability and toxicity should provide an opportunity to reconnect the wider fields of fire safety and fire chemistry. Given the complexity of toxicity, it is unlikely to feature in statutory guidance in the near future, but there is an opportunity to begin work exploring this.

6. REFERENCES

[1] H. de Lumley, Il y a 400 000 ans : la domestication du feu, un formidable moteur d'hominisation. *Comptes Rendus Palevol*, Vol 5, Iss 1–2, pp. 149-154, 2006.

[2] Tacitus, The Annals of Imperial Rome. Translated by Michael Grant and first published in this form in 1956. (London: The Folio Society, 2006).

[3] P. Meadows (Ed), *A Source Book of London history from the Earliest Times to 1800.* London: G. Bell and Sons, Ltd, 1914.

[4] J. Stow, A Survey of London. 1603.

[5] T. F. Reddaway, The Rebuilding of London after the Great Fire. London, 1940.

[6] An Act for the Rebuilding of the City of London (18-19 Chas. II. c. viii)

[7] http://www.history.ac.uk/gh/fire.htm – last accessed 19th October 2013

[8] http://www.london-fire.gov.uk/AnniversaryTooleyStreetFire.asp – last accessed 19th October 2013

[9] James Braidwood. On the Construction of Fire-Engines and Apparatus, The Training of Firemen, and the Method of Proceeding in Cases of Fire, 2nd Edition. Edinburgh 2004.

[10] Metropolitan Fire Brigade Act 1865 (28 & 29 Vic. c. xc).

[11] H.L. Malhotra, *Fire Safety in Buildings.* Building Research Establishment Report BR06, 1986.

[12] http://www.aim25.ac.uk/cats/118/17180.htm – last accessed 19th October 2013

[13] http://www.bre.co.uk/page.jsp?id=1712 – last accessed 2nd February 2014

[14] Building Act 1984 (c. 55)

[15] Building Regulations 2010, SI 2010 No 2214

[16] Regulatory Reform (Fire Safety) Order 2005, SI 2005 No 1541

[17] Fire and Rescue Services Act 2004 (c. 21)

[18] D. Drysdale, *Introduction to Fire Dynamics, Second Edition.* Chichester: Wiley, 1998.

[19] B. Karlsson and J. Quintiere, *Enclosure Fire Dynamics.* Boca Raton: CRC Press, 2000.

[20] British Standards Institute, *BS7974 Application of fire safety engineering principles to the design of buildings – Code of practice*, 2001.

[21] British Standards Institute, *BS5588 Fire precautions in the design, construction and use of buildings. Part 0. Guide to fire safety codes of practice for particular premises/applications,* 2001.

[22] British Standards Institute, *BS9999 Code of practice for fire safety in the design, management and use of buildings,* 2008.

[23] A Course of Six Lectures on the Chemical History of a Candle: To which is Added a Lecture on Platinum, Michael Faraday - 1 January 1861, Harper & Brothers 1861.

[24] P.B. Sunderland, J.G. Quintiere, G.A. Tabaka, D. Lian, C.-W. Chiu. *Analysis and measurement of candle flame shapes.* Proceedings of the Combustion Institute, Volume 33, Issue 2, 2011, Pages 2489-2496.

[25] P.L. Kirk, *Fire Investigation.* Chichester: Wiley, 1969.

[26] British Standards Institute, BS 7899 Part 2 *Code of practice for assessment of hazard to life and health from fire. Guidance on methods for the quantification of hazards to life and health and estimation of time to incapacitation and death in fires.* 1999.

[27] M. P. Shipp, The use of laboratory reconstruction in fire investigation, in N. Nic Daéid (Ed), *Fire Investigation,* London: CRC Press, 2004.

[28] W. D. Woolley, S. A. Ames and P. G. Smith, The Manchester Woolworth's store fire, May 1979: Burning characteristics of the furniture, *Fire Safety Journal,* Volume 3, Issue 1, pp. 55-65, 1980.

[29] British Standards Institute, BS ISO/TR 13387 Part 2 *Fire safety engineering. Design fire scenarios and design fires.* 1999.

[30] British Standards Institute, BS ISO/TR 13387 Part 4 Fire safety engineering. Initiation and development of fire and generation of fire effluents. 1999.

[31] B. Karlsson, Models for calculating flame spread on wall lining materials and the resulting heat release rate in a room, *Fire Safety Journal,* Volume 23, Issue 4, pp. 333-453, 1994.

[32] R. D. Peacock, P. A. Reneke, C. L. Forney and M. M. Kostreva, Issues in evaluation of complex fire models, *Fire Safety Journal,* Volume 30, Issue 2, pp. 103-136, 1998.

[33] R. Peacock, W. Jones, P. Peneke and G. Gorney, *CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 6) User's Guide.* National Institute of Standards and Technology US Department of Commerce, 2008.

[34] D. Fennel, *Investigation into the King's Cross Underground Fire,* The Department of Transport, Her Majesty's Stationery Office, London,1988.

[35] G. Cox, R. Chitty and S. Kumar, Fire modelling and the King's Cross fire investigation, *Fire Safety Journal,* Volume 15, pp. 103-106, 1989.

[36] K. Moodie and S. Jagger, *Fire at King's Cross Underground Station, 18 September 1987,* Health and Safety Executive 1987.

[37] N. C. Markatos, M. R. Malin and G. Cox, Mathematical Modelling of Buoyancy - Induced Smoke Flow in Enclosures, *International Journal of Heat and Mass Transfer,* 25, pp 63-75, 1982.

[38] G. Cox, S. Kumar and N. C. Markatos, Some Field Model Validation Studies, *Fire Safety Science, Proceedings of the First International Symposium,* Hemisphere, pp 159-171, 1986.

[39] G. Cox and S. Kumar, Modelling enclosure fires using CFD modelling, *SFPE Handbook, 3rd Edition,* National Fire Protection Association, USA, 2001.

[40] United States Nuclear Regulatory Commission, *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 7: Fire Dynamics Simulator (FDS), Final Report May 2007,* U.S. Nuclear Regulatory Commission, USA, 2007.

[41] *Santos v. State Farm Fire and Casualty Company, N.Y.S.2d, 2010 WL 2610656*, N.Y. Sup. Ct. 2010.

[42] R. G. Gann, V. Babrauskas, R. D. Peacock and J.R. Hull, Fire Conditions for Smoke Toxicity Measurement, *Fire and Materials,* Volume 18, pp. 193-199, 1994.

[43] J.H. Petajan, K.J. Voorhees, S.C. Packham, R.C. Baldwin, I.N. Einhorn, M.L. Grunnet, B.G. Dinger and M.M. Birky, *Extreme toxicity for combustion products of a fire-retarded polyurethane foam.* Science 1975, Vol 187, pp. 742-744.

[44] D. Wesolek and R. Kozlowski, Toxic Gaseous Products of Thermal Decomposition and Combustion of Natural and Synthetic Fabrics with and without Flame Retardant, *Fire and Materials,* Volume 26, pp. 215-224, 2002.

[45] British Standards Institute, *BS ISO 19706 Guidelines for assessing the fire threat to people,* 2011.

[46] K. N. Palmer, W. Taylor and K. Paul, *Fire hazards of plastics in furniture and furnishing- fires in furnished rooms,* Current Papers CP 21/76 & 3/75, Building Research Establishment, Garston, UK, 1976.

[47] British Standards Institute, *BS 5852 Methods of test for assessment of the ignitability of upholstered seating by smouldering and flaming ignition sources* 2006.

[48] The Furniture and Furnishings (Fire) (Safety) Regulations 1988, SI 1988 No. 1324, Crown Copyright, 1988.

[49] British Standards Institute, *BS 476 Part 3 Fire tests on building materials and structures. Classification and method of test for external fire exposure to roofs.* 2004.

[50] British Standards Institute, *BS 476 Part 7 Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products.* 1997.

[51] British Standards Institute, *BS 476 Part 4 Fire tests on building materials and structures. Non-combustibility test for materials.* 1970.

[52] British Standards Institute, *BS 476 Part 6 Fire tests on building materials and structures. Method of test for fire propagation for products.* 1989 + Appendix A1, 2009.

[53] British Standards Institute, *BS 476 Part 11 Fire tests on building materials and structures. Method for assessing the heat emission from building materials.* 1982.

[54] British Standards Institute, *BS EN 13501 Part 1 Fire classification of construction products and building elements. Classification using test data from reaction to fire tests.* 2007 + Appendix A1, 2009.

[55] British Standards Institute, *BS EN 13501 Part 6 Fire classification of construction products and building elements. Classification using data from reaction to fire tests on electric cables.* 2014.

[56] British Standards Institute, *BS EN ISO 1182 Reaction to fire tests for products. Non-combustibility test.* 2010.

[57] British Standards Institute, *BS EN ISO 1716 Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value).* 2010.

[58] British Standards Institute, *BS EN 13823 Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item.* 2010.

[59] British Standards Institute, *BS EN ISO 11925 Part 2 Reaction to fire tests. Ignitability of products subjected to direct impingement of flame. Single-flame source test.* 2010.

[60] British Standards Institute, *BS EN ISO 9239 Part 1 Reaction to fire tests for floorings. Determination of the burning behaviour using a radiant heat source.* 2010.

[61] British Standards Institute, *BS EN ISO 50399 Common test methods for cables under fire conditions – Heat release and smoke production measurement on cables during flame spread test – Test apparatus, procedures, results.* 2011.

[62] British Standards Institute, *BS EN 60332 Part 1-2 Tests on electric and optical fibre cables under fire conditions – Test for vertical flame propagation for a single insulated wire or cable – procedure for 1 kW pre-mixed flame.* 2004.

[63] British Standards Institute, *BS 476 Part 15, ISO 5660 Part 1 Fire tests on building materials and structures. Method for measuring the rate of heat release of products.* 1993.

[64] The Lancet Special Analytical Sanitary Commission on Smoke Prevention and Perfect Combustion.: III.—Gaseous Fuel, Gas-Heating and Gas-Cooking Appliances. *The Lancet*, Volume 142, Issue 3665, 25 November 1893, pp 1326-1336.

[65] Fire Research Station. *B.F.P.C. "Red Books".* Year unknown.

[66] Fire Research Station. "Red Books of the British Fire Prevention Committee. Year unknown.

[67] http://www3.gendisasters.com/ohio/2728/cleveland,-oh-clinic-explosion-fire,-may-1929 – last accessed 27 October 2013.

[68] I. N. Einhorn and M.L. Grunnet, Physiological and Toxicological Aspects of Combustion of Natural and Synthetic Materials: Past, Present and Future, *Fire Research,* 1977, Vol 1, pp.143-169

[69] J.C. Olsen, A.S. Brunjes and V.J. Sabetta, Gases Produced by the Decomposition of Nitrocellulose and Cellulose Acetate Photographic Films, *Industrial and Engineering Chemistry,* 1930, Vol 22, No 8, pp.860-863.

[70] Y. Henderson and H.W. Haggard, *Noxious Gases and the Principles of Respiration Influencing Their Action, Second Edition,* New York: Rheinhold, 1943.

[71] F.E.T. Kingman, *The Gaseous Products of Decomposition of Cellulose Nitrate-Cellulose Acetate Mixtures.* Fire Research Note 16, 1952.

[72] E.H. Coleman and P.H. Thomas. *Examination of the Products of Combustion of a Chlorinated Methyl Methacrylate.* Fire Research Note 52, 1951.

[73] P.H. Thomas, *Ventilation Requirements for Fires in Multi-Storey Flats Part I - Smoke and Gas Concentrations Likely to Occur.* Fire Research Notes 274 1956

[74] L.A. Ashton, *Movement of Smoke and Toxic Gases in Fires in Buildings.* Fire Research Note 434, 1960.

[75] The Building Regulations 1965, SI 1965 No. 1373, Crown Copyright, 1965.

[76] The Building Regulations 2010 Approved Document B (Fire Safety), 2006 Edition incorporating 2007, 2010 and 2013 amendments, Department for Communities and Local Government, Crown Copyright, 2013.

[77] Y. Tsuchiya and K. Sumi, Thermal decomposition products of polyvinyl chloride. *Journal of Applied Chemistry,* 17, pp. 364 London, 1967.

[78] G.C. Ackroyd, Plastics in buildings and fire insurance, *Plastics in Building Structures,* pp. 33–35, 1966.

[79] L.A. Ashton, Fire regulations and plastics, *Plastics in Building Structures,* pp. 27–31, 1966.

[80] A.J. Kelly, *Atmospheres from Fires in Rooms with Little Ventilation Part 1.* Fire Research Note 494, 1962.

[81] G.W. Stark and S.M. Hasan, *The Assessment of Smoke Production by Building Materials in Fires 1. Preliminary Measurements of Smoke Production in Fire Propagation Apparatus.* Fire Research Note 660, 1967.

[82] P.C. Bowes and P. Field, *The Assessment of Smoke Production by Building Materials in Fires 2. Test Method Based on Smoke Accumulation in a Compartment.* Fire Research Note 749, 1969.

[83] P.C. Bowes, P. Field and G. Ramachandran, *The Assessment of Smoke Production by Building Materials in Fires 3. The Effect of Relative Humidity on Measurements of Smoke Density.* Fire Research Note 775, 1969.

[84] G. W. Stark, W. Evans, and P. Field, *Toxic Gases from Rigid Poly (Vinyl Chloride) in Fires.* Fire Research Note 752, 1969.

[85] K. A. Scott, Fire performance of plastics in building, *British Polymer Journal,* Volume 2, Issue 4, pp. 244–248, 1970.

[86] W.D. Woolley and P.J. Fardell, The prediction of combustion products, *Fire Research,* Volume 1, Issue 1, March 1977, pp. 11–21.

[87] B.W. Mapperley and P.R. Sewell, The evolution of toxic gases from heated polymers — I. Hydrogen cyanide and carbon monoxide, *European Polymer Journal,* Volume 9, Issue 12, pp. 1255–1264, 1973.

[88] I. N. Einhorn, D. A. Chatfield, K. J. Voorhees, F. D. Hileman, R. W. Mickelson, S. C. Israel, J. H. Futrell and P. W. Ryan, A Strategy for Analysis of Thermal Decomposition of Polymeric Materials, *Fire Research,* 1977, Vol 1, pp. 41-56.

[89] W. D. Woolley, *A Study and Toxic Evaluation of the Products from the Thermal Decomposition of PVC in Air and Nitrogen.* Fire Research Note 769, 1969.

[90] W. D. Woolley and F. N. and Wrist, *Coupled Gas Chromatography – Mass Spectrometry and its Application to the Thermal Decomposition Products of Cellulose.* Fire Research Note 870, 1971.

[91] W.D. Woolley, A. I. Wadley and P. Field, *Studies of the Thermal Decomposition of Flexible Polyurethane Foams in Air.* Fire Research Note 951, 1972.

[92] W. D. Woolley and P. J. Fardell, Basic Aspects of Combustion Toxicology, Fire Safety Journal, Volume 5, Issue 1, pp. 29-48, 1982.

[93] A. Blahúšková, J. Mácha, A. Markoš, Z. Procházková and B. Štefl, Combustion Products of Polymeric Materials IV – Testing of Toxicity Hazard, *Fire and Materials,* Volume 10, pp. 1-6, 1986.

[94] D. A. Purser, P. Grimshaw and K. R. Berrilla, Intoxication by Cyanide in Fires: A Study in Monkeys using Polyacrylonitrile, *Archives of Environmental Health: An International Journal.* Volume 39, Issue 6, 1984, pp. 394-400.

[95] D. A. Purser and W.D. Woolley, Biological Studies of Combustion Atmospheres, *Journal of Fire Sciences*. March 1983, vol. 1, no. 2, pp. 118-144.

[96] G. E. Hartzell, Criteria and methods for evaluation of toxic hazard, *Fire Safety Journal,* Volume 12, Issue 3, pp. 179-182, 1987.

[97] G. E. Hartzell, Overview of combustion toxicology, *Toxicology,* Volume 115, pp. 7-23, 1996.

[98] Panel discussion, Smoke toxicity standard test method for materials, *Toxicology,* Volume 115, pp. 201-222, 1996.

[99] V. Babrauskas, R. G. Gann, B. C. Levin, M. Paabo, R. H. Harris, R. D. Peacock and S. Yusa, A methodology for obtaining and using toxic potency data for fire hazard analysis, *Fire Safety Journal,* Volume 31, pp. 345-358, 1998.

[100] F. B. Clarke and J. R. Hoover, Situational smoke toxicity testing: hazard assessment as the 'front end' of a smoke toxicity test, *Toxicology,* Volume 115, pp. 179-184, 1996.

[101] V. Babrauskas, Designing products for Fire Performance: the State of the Art of Test Methods and Fire Models, *Fire Safety Journal,* Volume 24, pp. 219-312, 1995.

[102] V. Babrauskas, The Generation of CO in Bench-scale Fire Tests and the Prediction for Real-scale Fires, *Fire and Materials,* Volume 19, pp.205-213, 1995.

[103] V. Babrauskas, Describing Product Performance – Manufacturers' versus Modelers' Needs, *Fire and Materials,* Volume 18, pp. 289-296, 1994.

[104] D. A. Purser, P. J. Fardell, J. Rowley, S. Vollam and B. Bridgeman, An improved tube furnace method for the generation and measurement of toxic combustion products under a wide range of fire conditions. Proceedings of the Flame Retardants '94 Conference, London, UK. January 1994. pp. 263–274. London, 1994.

[105] International Organization for Standardization, *ISO 19702 Toxicity testing of fire effluents - Guidance for analysis of gases and vapours in fire effluents using FTIR gas analysis.* 2006.

[106] D. Williams and I. Fleming, *Spectroscopic Methods in Organic Chemistry, 6th Edition.* London: McGraw-Hill Higher Education, 2008.

[107] K. Kinsella, J. R. Markham, C. M. Nelson and T. R. Burkholder, Thermal Decomposition Products of Fiberglass Composites: A Fourier Transform Infrared Analysis, *Journal of Fire Sciences,* 1997, Vol 15, pp. 108-125.

[108] International Organization for Standardization, *ISO 13571 Life-threatening components of fire — Guidelines for the estimation of time available for escape using fire data.* 2007.

[109] British Standards Institute, BS ISO 13344 Estimation of the lethal toxic potency of fire effluents. 2004.

[110] D. A. Purser, Asphyxiant components of fire effluents, in A. A. Stec and T. R. Hull (Eds) Fire Toxicity, Woodhead Publishing, 2010.

[111] D. A. Purser, Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat, in P. J. DiNenno, *The SFPE Handbook of Fire Protection Engineering, 4th Edition,* National Fire Protection Association, USA, 2008.

[112] T. R. Hull and K. T. Paul, Bench-scale assessment of combustion toxicity – A critical analysis of current protocols, *Fire Safety Journal,* Volume 42, Issue 5, pp. 340-365, 2006.

[113] British Standards Institute, *BS EN ISO 5659 Part 2 Plastics. Smoke generation. Determination of optical density by a single-chamber test.* 2012.

[114] T. R. Hull, Bench scale generation of fire effluents, in A. A. Stec and T. R. Hull (Eds) Fire Toxicity, Woodhead Publishing, 2010.

[115] Association Francais de Normalisation, *NF X 70-100 Partie 1, Essais de comportement au feu - Analyse des effluents gazeux - Partie 1 : méthodes d'analyses des gaz provenant de la dégradation thermique.* 2006.

[116] Association Francais de Normalisation, *NF X 70-100 Partie 2, Essais de comportement au feu - Analyse des effluents gazeux - Partie 2 : méthode de dégradation thermique au four tubulaire.* 2006.

[117] British Standards Institute, *BS 7990 Tube furnace method for the determination of toxic product yields in fire effluents.* 2003.

[118] International Organization for Standardization, *ISO/TS 19700 Controlled equivalence ratio method for the determination of hazardous components of fire effluents.* 2007.

[119] A. Tewarson, Ventilation effects on combustion products, *Toxicology,* 1996, Vol 115, pp. 145-156.

[120] British Standards Institute, *BS ISO TR 9705 Part 2 Reaction to fire tests. Full scale room tests for surface products. Technical background and guidance.* 2001.

[121] G. E. Hartzell, D. N. Priest and W. G. Switzer, Modeling of toxicological effects in fire gases: Mathematical modelling of intoxication of rats by carbon monoxide and hydrogen cyanide. *Journal of Fire Sciences,* Volume 3, pp. 115-128, 1985.

[122] https://www.gov.uk/government/organisations/department-for-communities-and-local-government/series/fire-statistics-great-britain – last accessed 26 August 2013.

[123] Gross Domestic Product data since 1955, collated by The Guardian online, http://www.theguardian.com/news/datablog/2009/nov/25/gdp-uk-1948-growth-economy - last accessed 3rd November 2013.

[124] G. G. Auber, J. Walters, D. W. Millar, and J. F. Fry, *Statistical Analysis of Reports of Fires Attended by Fire Brigades in the United Kingdom During 1951.* Fire Research Note 43, 1952.

[125] S. E. Chandler, *Preliminary Analysis of Fire Reports from Fire Brigades in the United Kingdom, 1967.* Fire Research Note 702, 1968.

[126] S. E. Chandler, *A Survey of Multiple Fatality Incidents, 1960-1966.* Fire Research Note 703, 1968.

[127] *Report of the Tribunal of Inquiry on the Fire at the Stardust, Artane, Dublin on the 14th February,1981.* Dublin: The Stationery Office, 1982.

[128] G.R. Nice, H.L. Malhotra, P.L. Hinkley and W.D. Woolley, *Artane Fire Tribunal – Report of the Special Investigation on behalf of the Tribunal by the Fire Research Station of the Building Research Establishment,* BRE 1981.

[129] http://arohatgi.info/WebPlotDigitizer/ - last accessed 11th August 2013

[130] H.R.C. Boyce, *Fire at the Maysfield Leisure Centre Belfast on 14th January 1984.* Department of Economic Development (Northern Ireland), Crown Copyright 1984.

[131] W.D. Woolley, A.W. Williams, S.A. Ames, H.P. Morgan, G. Cox, P.J. Fardell, S.P. Rogers and M.G. Lunt, *Fire in the Maysfield Leisure Centre, Belfast, January 1984 Studies of the Burning Characteristics of Gymnastic Materials.* Fire Research Station report, 1984.

[132] http://arohatgi.info/WebPlotDigitizer/ - last accessed 11th August 2013

[133] D. A. Purser, Behavioural impairment in smoke environments. *Toxicology,* Volume 115, pp. 25-40, 1996.

[134] Sheriff Principal B.A. Lockhart, *Sheriffdom of South Strathclyde Dumfires and Galloway under the Fatal Accidents and Sudden Deaths Inquiry (Scotland) Act 1976, Determination by Sheriff Principal Brian A Lockhart in Respect of the Inquiry into the Deaths of Annie (Nan) Stirrat, Julia McRoberts, Robina Worthington Burns, Isabella MacLeod, Margaret Lappin, Mary McKenner, Ellen (Helen) Veronica Milne, Helen (Ella) Crawford, Annie Florence Thomson, Margaret Dorothy (Dora) McWee, Thomas Thompson Cook, Agnes Dennison, Margaret McMeekin Gow and Isabella Rowlands MacLachlan,* Crown Copyright 2011. Available from http://www.scotcourts.gov.uk/opinions/2011FAI18.pdf

[135] M.P. Shipp, P. Field, D.A. Purser, J. Purser, R. Colwell and P. Clark, *Experimental research for Scottish Building Standards Agency following the fire at the Rosepark Care Home, Glasgow, 31st January 2004,* Crown Copyright 2011. Available from http://www.scotland.gov.uk/Resource/Doc/175356/0119308.pdf

[136] Hertfordshire Fire and Rescue Service, *Investigation into the deaths of Firefighter Jeremy Wornham, Firefighter Michael Miller and Ms Natalie Close at 85 Harrow Court, Silam Road, Stevenage, Hertfordshire on Wednesday 2nd February 2005, call number 1693.* Available from http://www.hertsdirect.org/infobase/docs/pdfstore/harctreport.pdf

[137] *Inquisition at the Old Courthouse, Hatfield in the County of Hertfordshire on the 7th day of February 2005 and by adjournment on the 17th day of February 2007 at the Old Courthouse, Hatfield in the County of Hertfordshire before and by Edward Gordon Thomas Her Majesty's Coroner for the District of Hertfordshire.* Crown Copyright 2007. Available from http://www.fbuberkshire.co.uk/wp-content/uploads/2011/01/Harrow_Court_5_Inquest_Verdict.pdf

[138] R. Colwell, *Fire at Harrow Court, Stevenage, 2nd February 2005: Full-scale room and corridor fire reconstruction,* BRE Report number 227283 prepared for Hertfordshire Fire and Rescue Service. Copyright BRE 2006.

[139] R. Chitty, D. A. Purser and M. P. Shipp, *Harrow Court Fire Investigation: Numerical Modelling and Airflow Measurements,* BRE Report number 227787 prepared for Hertfordshire Fire and Rescue Service. Copyright BRE 2006.

[140] D. Crowder, R. Chitty, M. Shipp and R. Cullinan, *Lakanal House Fire Investigation - Computer modelling and reconstruction fire,* BRE Report number 259449 prepared for London Fire Brigade. Copyright BRE 2010.

[141] http://www.lambeth.gov.uk/elections-and-council/lakanal-house-coroner-inquest - last accessed 18th May 2014.

[142] Private communication from D. Crowder photographic records.

[143] Private communication from D. Crowder reconstruction data records.

[144] British Standards Institute, *BS ISO 19701 Methods for sampling and analysis of fire effluents.* 2005.

[145] V. Babrauskas, *Ignition Handbook,* USA: Fire Science Publishers, 2003.

[146] S. Kumar, *Fire Modelling with Computational Fluid Dynamics,* BRE Digest 511, 2009.

[147] D. J. C. MacKay, Sustainable Energy – without the hot air, UIT 2008.

[148] Bureau Veritas UK, *London Fire Brigade Fire Risk Assessment of Multi-Layer Paints – Lakanal House, 18 August 2010.* 2010.

[149] British Standards Institution, *PD 7974 Part 1: 2003 Application of fire safety engineering principles to the design of buildings. Initiation and development of fire within the enclosure of origin (Sub-system 1),* 2003.

[150] Building Regulations 1972, SI 1972 No. 317.

[151] CIBSE Guide C: Reference Data, The Chartered Institution of Building Services Engineers, London, 2007.

[152] British Standards Institution, PD 7974 Part 6: 2004 The application of fire safety engineering principles to fire safety design of buildings. Human factors. Life safety strategies. Occupant evacuation, behaviour and condition (Sub-system 6), 2004.

[153] D. Crowder and R. Chitty, *Atherstone-on-Stour Fire Reconstruction and Modelling Final Research Report*, BRE Report number 275178 prepared for Warwickshire Fire and Rescue Service. Copyright BRE 2012.

[154] T. Jin, *Visibility through fire smoke.* Building Research institute, Tokyo, Reports number 30 and 33. 1970, 1971.

APPENDIX A – LETTER OF PERMISSION FROM BRE

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bre

Dr Richard McCabe
Centre for Material's Science
University of Central Lancashire
Preston
PR1 2HE

30 May 2014

Dear Dr McCabe

David Crowder has been an employee of BRE throughout the duration of his thesis and BRE has sponsored his studies by covering the costs of his University fees. His work has included carrying out detailed reviews of fires which BRE and its staff (some as the then Fire Research Station) have worked upon. These fires are as follows:

- The Stardust Disco fire on 14th February 1981
- The Maysfield Leisure Centre fire on 14th January 1984
- The Rosepark Care Home Fire on 31st January 2004
- The Harrow Court fire on 2nd February 2005
- The Atherstone on Stour Fire on 2nd November 2007
- The Lakanal Fire on 3rd July 2009

All of the work carried out by BRE on these fires has been for a client or government department, so BRE does not hold sole rights to any of the work. I understand that David has either used material which is either subject to Crown Copyright and so may be used as part of academic study, or has sought express permission from clients to use work completed for them. On behalf of BRE, I am satisfied that, subject to the foregoing, permission is given for David to use material for which BRE holds intellectual property rights and copyright.

Yours sincerely

D A Smith

Dr D A Smith OBE
Director, Fire Sciences and Building Products
For and on behalf of BRE Global

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Mobile: +44(0)7772 228715
E-mail: smithda@bre.co.u

APPENDIX B – LETTER OF PERMISSION FROM METROPOLITAN POLICE SERVICE

Crowder, David (Fire & Security)

From:	Rick.Murphy@met.pnn.police.uk
Sent:	29 May 2014 16:21
To:	Crowder, David (Fire & Security)
Cc:	Vanessa.Cooper@met.pnn.police.uk
Subject:	Lakanal Fatal Fire 2009
Follow Up Flag:	Follow up
Flag Status:	Flagged

Dear Dave,

As you are aware I was the Senior Investigating Officer for the MPS in relation to the Fatal Lakanal Fire in 2009 and you have asked for permission to use material in a thesis. I have consulted with the MPS legal team and this permission is given under the following terms:-

'David Crowder has worked with the Metropolitan Police Service throughout the investigation of the fire at Lakanal on 3rd July 2009. His work has included investigation into the way in which the fire developed and spread during the course of the incident and how this led to the deaths of the six victims. This work was presented during the inquest into the fire which took place in early 2013 and is detailed within BRE report number 259441 (dated 17th December 2010).

On behalf of the Metropolitan Police Service, I am satisfied that permission is given for David to use the material contained within BRE report number 259441 for the purpose of completing his thesis. I am content that some work from this report is included in chapter 3.1 and that this will include figures (Figures 49 to 139) produced by David and by other investigators from the Metropolitan Police Service, provided suitable attribution is made.

There are ongoing legal proceedings regarding the fire at Lakanal so permission is provided with the caveat that the thesis and all materials pertaining to Lakanal must be kept confidential for two years following the completion of the thesis or the end of the legal proceedings if longer than two years. I understand that no material proportioning blame is to be included in this thesis. In addition the material when it is published will be brought to my attention before this occurs'

Kind regards,

Rick Murphy
Detective Inspector
Sexual Offences, Exploitation and Child Abuse Command
SCO2 Team 4
1 Cam Road
Stratford
E15 2SY
Mobile:07917520832
EMail: rick.murphy@met.police.uk

APPENDIX C – LETTER OF PERMISSION FROM LONDON FIRE BRIGADE

LONDON FIRE
AND EMERGENCY
PLANNING AUTHORITY

169 Union Street London SE1 OLL
T 020 8555 1200 F 020 7960 3603
Minicom 020 7960 3629
www.london-fire.gov.uk

London Fire and Emergency Planning
Authority runs the London Fire Brigade

Date 29 May 2014
Our Ref LEGAL/AFP/7876/YM
Your Ref

Dear Sir

David Crowder has worked with London Fire and Emergency Planning Authority (the Authority) throughout the investigation of the fire at Lakanal on 3rd July 2009. His work has included investigation into the way in which the fire developed and spread during the course of the incident and how this led to the deaths of the six victims. This work was presented during the inquest into the fire which took place in early 2013 and is detailed within BRE report number 259449 (dated 17th December 2010).

Subject to the provisos set out below, the Authority hereby permits David Crowder to reproduce material contained within BRE report number 259449 in his thesis , provided suitable attribution is made in the thesis in respect of the Authority.

There are ongoing legal proceedings regarding the fire at Lakanal so permission is granted subject to the additional proviso that the thesis and all materials pertaining to Lakanal be kept confidential for two years following the completion of the thesis or the completion of all legal proceedings (whichever is the later).

Yours faithfully

Linda Armstrong
Deputy Head of Legal and Democratic Services

Reply to Yvonne McKenna
Direct **T** 020 8555 1200 x30124
Direct **F** 020 7960 3617
E yvonne.mckenna@london-fire.gov.uk

APPENDIX D – LETTER OF PERMISSION FROM WARWICKSHIRE FIRE AND RESCUE SERVICE

Our Ref: ACFO/18-14/DTM

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Dr Richard McCabe
Centre for Material's Science
University of Central Lancashire
PRESTON
PR1 2HE

23rd May 2014

Dear Dr McCabe

PHD THESIS - DAVID CROWDER

David Crowder has worked closely with Warwickshire Fire and Rescue Service over the last three years providing expert advice, fire simulations and modelling, to help explain the circumstances around the tragic fire in Atherstone on Stour on 2nd November 2007.

David's work was detailed and robustly prepared to withstand the scrutiny of a Crown Court setting. I believe that the research, analysis and reporting that David completed for our investigation will add depth to his thesis. On behalf of Warwickshire Fire and Rescue Service, I am satisfied that permission is given for him to use information obtained through the investigation to support his studies and as content for his thesis. I understand that London Fire Brigade have also granted this permission with a caveat that it is not published for two years, I believe that this is an appropriate control measure for Warwickshire also.

We wish David all the very best wishes with his studies.

Yours sincerely

Jim Onions
Assistant Chief Fire Officer

INVESTOR IN PEOPLE