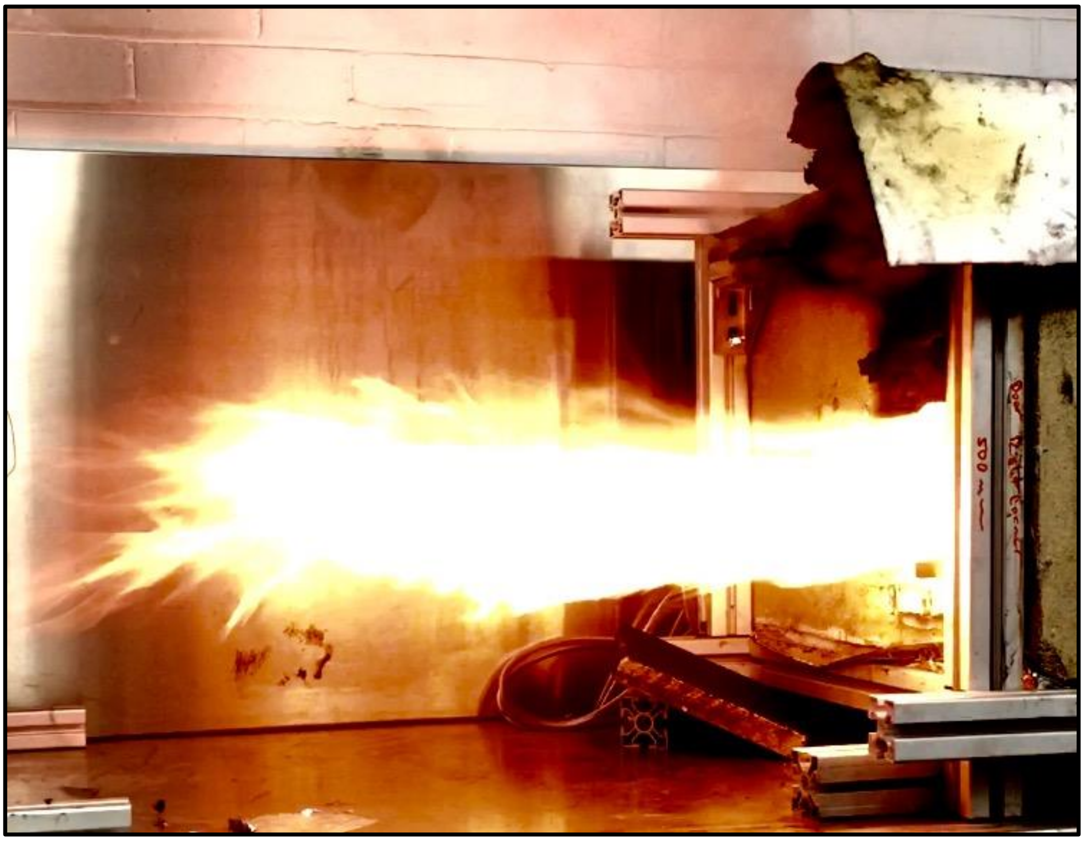
BRE CENTRE *for* FIRE SAFETY ENGINEERING
THE UNIVERSITY *of* EDINBURGH

Strategies for fire-fighting in basements: FINAL REPORT



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Executive Summary

A final report of the "*Strategies For Fire-Fighting In Basements*" project is presented.

The main relevant works concerning basement fires and backdraught which have been identified in the literature are listed and summarised.

Initial experimental work (WP1) is described and discussed. Four modes of burning behaviour are identified and the conditions under which they may exist are defined.

The outcome of preliminary discussions with various fire brigades (WP2) are discussed. The main conclusions so far are:

- Formal cooperation has been established with London Fire Brigade and the Scottish Fire & Rescue Service.
- This cooperation has *already* led to proposed changes in LFB's Policy Notes.
- Informal contact has been made with other fire services across Europe.
- Operational practices regarding fires in basements have been reviewed. In general, the operational guidance is not to ventilate or let the fire ventilate itself naturally.

Experimental results using a larger, two room, basement apparatus (WP3) are presented. A test setup and procedure has been defined which promotes conditions which consistently lead to flashover and backdraught in the apparatus.

- It is shown that backdraught conditions can generally be avoided by opening both vents in quick succession, creating a cross-flow situation.
- In situations where cross-flow ventilation cannot be used, dilution may be the best mitigation technique. This requires further research beyond the current project.

Operational guidance, journal papers and conference presentations (WP4) are in preparation for presentation beyond the end of the project.

1 BACKGROUND

Fires in basements remain an unresolved problem for fire brigades. While some brigades have specific guidance in place regarding procedures for approaching and fighting such fires, this guidance is, for the most part, based on anecdotal evidence, having been instigated following incidents involving fire-fighter injuries or fatalities.

2 PURPOSE

The proposed project aims to provide further scientific understanding of:

- broadly, under-ventilated fire dynamics in general, and
- specifically, the fire dynamics in basements when changes in ventilation conditions occur.

It is intended that these results will be used to develop simple guidance, which may be used in fire brigade practice, to decide when and how to intervene in basement fires.

3 BASIS OF THE UNDERLYING PHENOMENA

As fire-fighters enter an under-ventilated compartment fire, there is a risk of a sudden fire development that may come in the form of a rapid flare up or backdraught. This is why research has been and currently is focused on the understanding of these phenomena and the main factors which affect the:

A

- Likelihood
- Severity

Once the physical basis of the underlying phenomena is well understood, the knowledge can then be applied in two fundamental ways:

B

- A passive approach to the problem: Influencing Building Design
  - Knowledge is incorporated into new building regulations
- An active approach to the problem: Influencing Fire-fighting Tactics & Practices
  - Knowledge is incorporated into new and revised fire-fighter guidelines and manuals

These two objectives are actively linked as good building design should not only mitigate the effects of a potential rapid changes in burning behaviour, but also allow for reasonable fire-fighting strategies to be carried out.

The natural sequence of – *first* – thoroughly understating the physical phenomena (A), and then – *second* – translating the understanding into practical design and/or practice (B), is not always embraced. Unfortunately, development of activity (B) commonly occurs with no advances in (A).

4 RESEARCH TO DATE

In an effort to overcome the situation described above, this subsection summarises what mainstream research in under-ventilated compartment fires (e.g. basements) has found so far, including any recommendations made:

4.1 LITERATURE REVIEW/SURVEY ON BACKDRAUGHT

The following is a summary of the most relevant reports on the subject to date:

- ***A Survey of Backdraught – Main Report***, R. Chitty, BRE (FRS), Department for Communities and Local Government (DCLG), 1994.

  This report describes a survey of knowledge gathered before 1994 on backdraught and considers needs for any further research work and the implications for the training of fire-fighters.

  It emphasises the need for fire-fighters to understand the fundamental differences between a backdraught and a flashover, so that they can recognise potential conditions leading to either of the sudden events which represent a serious hazard for them. In this regard, it lists a series of potential indicators or warning signs which may lead to a backdraught.

  The report urges for the continued research into both flashover and backdraught as the basic requirement to support fire-fighting techniques, and enable building design which would mitigate the effects of a backdraught and allow fire-fighting strategies. It explicitly states that tactics such as venting and indirect/direct application of water cannot be used effectively and safety without an adequate understanding of the development of fires in both well and under-ventilated fires.

  Finally, this report exposes:

  - the need to clarify the scientific terminology,
  - the need for a simple and scientifically sound text available to the entire fire community,
  - the need for more realistic and practical training for the UK fire-fighters,
  - the need within the Fire Service for a sound education on all aspects of fire science, and
  - the lack of communication between fire scientists and fire-fighters.

- ***Fire-fighting in under-ventilated compartments: Literature Review***, Fire Research Technical Report 5/2005, B. Hume, Fire Statistics and Research Division, Office of Deputy Prime Minister (ODPM)[1]: London, December 2004.

  The project included a literature review of previous research, guidance and building regulations, an analysis of FDR1 statistics and a review of reported fire incidents involving backdraught.

  The review found that although a number of research projects had been carried out on backdraught in years previous to its publication, there was still some way to go before a sufficient understanding of backdraught and the factors that affect its likelihood of occurrence and severity (e.g. compartment sizes, smoke ventilation, smoke detection systems, and sprinklers systems) are accomplished. In this regard, it recommends further research to obtain a better understanding of the physical processes involved in backdraught.

  It also concludes that the venting of basements is a problem due to the lack of natural openings and a particular concern is the guidance on this in the UK Building Regulations that allows some spaces in basements to be vented indirectly by fire-fighters opening connecting doors. In this regard, it recommends that the Guidance in the Building Regulations on venting of basements should be reviewed, as this action is likely to be a particularly serious hazard to fire-fighters, leaving them vulnerable to a backdraught, with no easy exit.

  Within the same topic of venting basements, the report exposes that Approved Document B specifies a vent area for natural smoke outlets of 'not less than 1/40th of the floor area' for basements, for use by fire-fighters on arrival, and sates that this figure does not appear to be based on any documented evidence of its effectiveness. Therefore, it recommends that research by experiment, modelling or otherwise is done to determine whether this area allows for effective clearance of smoke, and whether there is a range of vent areas which allow for effective clearance of smoke and at the same time minimise the likelihood and severity of backdraught caused by opening the vent.

  The report exposes the fact that the regulations on ventilation have specified a level of background ventilation while, however, it was not determined – and this still applies today – what effect these factors have on a fire and on the likelihood and severity of a backdraught. In this regard, it recommends further investigation by experiment and modelling on background ventilation and insulation in modern buildings, to analyse their effect on the development of conditions which may cause a backdraught.

[1] On 5th May 2006 the responsibilities of the ODPM transferred to the DCLG

Finally, the report lists some recommendations made by H.P. Morgan – “Smoke Ventilation of Basements”, June 2004. These are:

- Large undivided volume basements are best protected by Smoke and Heat Exhaust Ventilation Systems (SHEVS) where the ceiling is high enough, but SHEVS solutions will usually require sprinklers to limit fire growth.
- Depressurisation as described in BS 5588-4[2] is the most effective option for protecting stairwells accessing basements, even more so than pressurisation described in the same standard. It is recommended that the present requirement for pressurising fire-fighting shafts deeper than 10 m (see BS 5588-5) be amended to allow and to encourage the depressurisation option being adopted.
- Sprinklers should be fitted in deeper basements.
- It is suggested that only powered exhaust should be allowed at ground level.
- All natural exhaust should be taken to the top of the building.

4.2 ACADEMIC REPORTS

- ***A CFD and experimental investigation of under-ventilated compartment fires***, Georges Guigay, 2008 PhD dissertation, Department of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland, Reykjavik, September 2008.

  The choice of fire-fighting tactics to use at the scene of a fire depends a lot on the situation the fire-fighters will face upon arrival there. In this dissertation (and related paper), commonly used tactics were selected, based on one of the co-author’s experience as a fire officer. Depending on the conditions, the particular risk of backdraught was considered, and CFD calculations were used to characterize the effects of these tactics on backdraught mitigation.

  To estimate this risk, this work lists the warning signs that can be observed as:

  - Pulsating gases in small gaps and openings.
  - Hot windows and doors indicate that temperatures are still high in the apartment allowing pyrolysation to take place.
  - No visible flame in the fire room.
  - Whistling sounds around doors and windows.

  If there is a serious risk of backdraught, the factors that will influence the choice of tactics are listed in this work as:

  - The most critical factor is whether there are people left inside the apartment or not. In a **lifesaving operation** the time factor is critical, and the fire-fighters will have to use the less time consuming measures.

[2] BS 5588 is now withdrawn and replaced with BS 9999.

        - In this situation the personnel is usually taking a higher risk since the attack is made with Breathing Apparatus (BA) team. The most important thing for the BA team is to cool the smoke gases as soon as fresh air is introduced in the apartment. The introduction of water spray has the effect of cooling the gases, creating a better environment for fire-fighters.
        - Positive Pressure Ventilation (PPV) may also be used in a lifesaving operation. The use of PPV can be very effective for the venting of flammable gases. However, it is very important that the air stream generated by the PPV fan has a clear path to the discharge opening. The danger of backdraught will increase significantly during the first seconds, but decrease very quickly. The use of PPV requires good knowledge and utilization experience. This work shows that incorrect use of PPV can greatly increase the risk of backdraught due to a long-lasting highly mixed situation.

    - In a situation where it has been confirmed that there is no-one left in the building, the use of a **defensive tactic** such as natural ventilation is very beneficial. This is clearly shown in the CFD calculations. The apartment can be vented both through the front door and e.g. a window on the back. There is a risk that the smoke gases may ignite outside the building and therefore, water extinguishing methods should be ready outside the opening. However, in defensive tactics, there is very low risk of human injuries.

  This work concludes that dilution is the dominant extinguishing mechanism, and the method of spraying water mist has proved very effective, provided that the dilution is sufficient. This means that the volume fraction of the unburnt gases is below the critical fuel volume fraction, as the danger of backdraught will be completely eliminated. It is important that as little fresh oxygen as possible is introduced during the water mist spraying, and therefore it is very beneficial to use tools such as piercing nozzles or cutting extinguishers. Nevertheless, if the volume fraction is still above this critical value, the danger of backdraught lasts much longer. Yet, fire-fighting manuals recommend dilution as a tactic to use on under-ventilated fires.

- ***Computer modelling of basement fires Part 1***, Fire Research Report 26/2008, and ***Part 2***, Fire Research Report 27/2008, S. Ferraris and J.X. Wen, Faculty of Engineering, Kingston University, Department for Communities and Local Government (DCLG), February 2009.

  The Building Regulations currently require certain buildings to have breakable ventilators at ground level to allow fire-fighters to ventilate basements. However, the guidance in the Fire Service Manual and associated Generic Risk Assessments, and for the Building Regulations does not make clear the circumstances under which these breakable ventilators (known as pavement lights) should be used by fire-fighters.

This research was undertaken to examine the effect on a fire in a basement and the danger to fire-fighters who are in the basement when a pavement light is broken.

The research used a combination of computer modelling and full-scale fire test data. Part 1 of the research undertook practical fire tests and used computer modelling to simulate fire behaviour and growth. Part 2 of the work undertook further computer modelling of specific factors such as the effect of positive pressure ventilation.

The two reports investigate the effect of providing venting to a basement fire, and provide evidence that venting of basements using pavement lights cannot be relied on as a safe practice for fire and rescue services to use during fire-fighting. They also conclude that venting of a basement compartment via a second compartment is not advisable.

The study therefore urges the fire and rescue services to take account of these findings for their own operational procedures and practices, and recommends that consideration be given to revision of the existing guidance in the Fire Service Manual – as well as to future revisions of the Building Regulations and associated design standards – to address the findings.

- ***Fire protection of basements and basement car park***, Work Stream 4, Final Work Stream Report BD 2887, R. Chitty and J. Fraser-Mitchell, BRE, Department for Communities and Local Government (DCLG), February 2015.

  The principal aim of this work was to produce robust evidence and data to explore the options for fire protection of basement generally and basement car parks specifically. It considered the background to the current guidance in relation to basements and basement car parks, and undertook new fire experiments with basement configurations.

  The report addresses the fact that the provisions in Approved Document B for basements and basement car parks relate to the following:

  - protecting structures supporting higher levels of the building during a fire,
  - means of escape, and
  - provision of access and facilities for fire-fighters.

  The relevant conclusions of this work are the following:

- Approved Document B currently includes recommendations for features intended to assist fire-fighters which cannot be used operationally due to uncertainties in their safe method of use.
- The review of the current fire statistics shows that there are a relatively small number of fires in basements and a low number of associated injuries.
- The project has provided additional data that can be used to validate fire modelling (as part of a fire engineered solution), as well as additional guidance, examining specifically the impact of increased insulation levels in buildings and – to a limited extent – the size and location of openings at ceiling level.
- The development of some simple solutions for inclusion in Approved Document B requires some further work and demonstration of performance in a range of different fire scenarios.

4.3 FIRE-FIGHTERS REPORTS/MANUALS

- ***An assessment of the effectiveness of removable pavement lights when fighting a basement fire***, J.G. Rimen, Home Office Fire Research and Development Group, FRDG Publication Number 6/95, London, 1995.

  This report describes a series of trials designed to assess the effectiveness of removable or breakable pavement lights or stallboards, in the event of a basement fire, and find an answer to the underlying question: "Are removable or breakable pavement lights or stallboards necessary, or even helpful, in fire-fighting operations?"

  Different scenarios were tested in the same basement, combining natural or forced (PPV) ventilation, together with pavement light open or shut.

  In these trials, the removal of the pavement light was seen to have a very slight beneficial effect with natural ventilation (although the benefit may have been more marked in different wind conditions). However, the report states that when a PPV fan was deployed, the benefits accruing from the removal of the pavement light were significant and almost immediate.

  Based on the following listed advantages of having a removable or breakable pavement light:

  - the ability to vent the fire without the need for smoke to have to permeate through the building above;
  - the (probable) reduction of temperatures in the basement and stairwell, aiding fire-fighting;
  - the reduction of smoke-logging in the building as a whole;

- the improvement in visibility in the basement, both by allowing smoke to escape, and by allowing some daylight (or artificial light) to enter into a, probably, smoke-blackened interior, aiding searching and fire-fighting;
- it can allow fire-fighters to get an idea of what is happening in the basement, without the need to enter the building and descend to the basement; and
- it can allow direct fire-fighting from outside the building, making possible an early attack using water or high expansion foam.

The report concludes that, from the point of view of the brigades, it is better to have removable or breakable pavement lights or stallboards than not to have them, since their existence gives a brigade an additional option which can give various benefits.

It is also important to mention that the report states that if the pavement light is removed and is seen to be having an adverse effect upon the situation, it may be possible to replace it, or blank it off. This statement is clearly disregarding the scenario of a sudden or violent change in the burning behaviour as a consequence of opening a ventilation path to an under-ventilated fire.

- ***Fire-fighting in Basements***, 3/2009, Dear Chief Officer (Scotland) Letter, Scottish Fire and Rescue Advisory Unit, 16 April 2009.

  This is a letter from the Head of the Scottish Fire and Rescue Advisory Unit directed to all the Chief Officers.

  The letter states that fires in basements may present a risk of backdraught or other rapid fire development, when fire-fighters open vents such as pavement lights and doors to begin fire-fighting or rescue, due to the lack of ventilation.

  It mentions that although the Technical Handbooks for compliance with Building Regulations contain provision for certain basement storeys to (a) have ventilation provided to assist fire-fighting operations and to allow smoke clearance after the fire and (b) for smoke outlets (windows, panels or pavement lights) communicating directly with the external air, the guidance in the Fire Service Manual and Generic Risk Assessments does not make clear the circumstances under which ventilators should be used by fire-fighters.

  The letter also makes reference to the research undertaken by Kingston University (presented in this report under section 4.2), urging the Fire and Rescue Services (FRSs) to take account of the findings of this research for their own operational procedures and practices. And literally lists the relevant conclusions of this study as:

  - Venting of basements using pavement lights cannot be relied on as a safe practice for fire and rescue services to use during fire-fighting. Successful venting during a fire is too dependent on wind and pressure conditions at the vent outlet and identification of the correct vent to operate. FRSs should use standard compartment entry tactics as recommended in the Fire Service Manual, keeping venting to a minimum, and should not use natural vents from basements until full extinguishment of the fire is confirmed or extinguishing media are ready for immediate use to control any possible fire development.

  - Similarly, venting of a basement compartment via a second compartment is not advisable as a safe practice for FRSs to use during fire-fighting.

Finally, the letter states that said research recommends that consideration be given to revision of the existing guidance in the Fire Service Manual to address the findings, and that this will be considered as part of the on-going development of an operational guidance framework.

- ***Compartment Fires and Tactical Ventilation***, Fire Service Manual, Volume 2, Fire Service Operations, issued under the authority of the Home Office, HM Fire Service Inspectorate, The Stationery Office (TSO), London, Fourth Impression, 2006.

The Tactical Ventilation part of this manual attempts to bring together all the existing advice available on the use of ventilation. As the manual explicitly states, this advice is based on fire-fighters' experience, good fire-fighting practice, and a sound understanding of the physics involved, but nevertheless it has yet to be supported by experimental verification.

The manual acknowledges the highly dangerous consequences of backdraughts, and describes the signs and symptoms that could potentially lead to triggering one after venting. However, for those situations where there is the possibility that a backdraught may occur during ventilation but the compartment still has to be inspected, the manual lists the appropriate precaution actions that fire-fighters should take, emphasising the fact that no compartment can be considered safe from a backdraught until it has been opened to fresh air for some time.

The manual points towards the wind strength and direction as the usual dominating factors in tactical ventilation. It stresses that, properly used tactical ventilation can have significant beneficial effects on fire-fighting, however if it is applied incorrectly, it can likewise make things worse.

The manual also describes that – if it is decided that tactical ventilation is required – two approaches can be taken:

  - *Offensive* – ventilating close to the fire to have a direct effect on the fire itself, to limit fire spread, and to make conditions safer for the fire-fighters; or

  - *Defensive* – ventilating away from the fire, or after the fire is out, to have an effect on the hot gases and smoke, particularly to improve access and escape routes and to control smoke movement to areas of the building not involved in the fire.

It is important to clarify that this research project is only concerned with what is defined by this manual as the offensive tactical ventilation; i.e. venting close to the fire and directly to the outside.

4.4 Summary of the Research to Date

The most relevant conclusions of the research to date on basement fires would then be:

- From the *Scientific* side:
  - There is a need to clarify the scientific terminology, as well as to express it in a simple and scientifically sound text.
  - There is a need for continued research into both flashover and backdraught as the basic requirement to support fire-fighting techniques and enable safer building design.
  - There is a need to communicate, exchange knowledge, and engage in joint research with the Fire Service.

- From the *Fire Service* side:
  - There is a need for more realistic and practical training for the fire-fighters.
  - There is a need within the Fire Service for a sound education on all aspects of fire science.
  - There is a need to communicate, exchange knowledge, and engage in joint research with the scientific community.

- From the *Regulatory* side:
  - There is a need to modify the regulations, specifically Approved Document B which currently includes recommendations for features intended to assist fire-fighters which cannot be used operationally due to uncertainties in their safe method of use.

This shows that from the *Building Design/Consulting* side there is also an urgent need to communicate, exchange knowledge, and engage in joint research with both the scientific community and the Fire Service.

Overall, all major research undertaken in basement fires – apart from one[3] – make clear that venting an under-ventilated fire through a single compartment side opening (e.g. through pavement lights or even via a second compartment) cannot be relied on as a safe practice for fire and rescue services to be used during fire-fighting.

Tactics such as venting and indirect/direct application of water cannot be used effectively and safely without an adequate understanding of the development of fires in both well and under-ventilated conditions.

5 PROGRAMME OF WORK – IMPLEMENTATION

As described in the proposal, the work was arranged in four overlapping work packages (WP):

WP1. Use existing small-scale (cubic) apparatus to investigate changes in ventilation on fire behaviour.
WP2. Discuss operational procedures, techniques and requirements with fire brigades.
WP3. Develop and use a larger-scale (elongated) apparatus to investigate fire behaviour in a more realistic (basement-like) geometry.
WP4. Develop operational guidance. Disseminate information.

5.1 WP1 OUTCOME

5.1.1 Aims & Objectives

To establish the controlling physical conditions of the different burning modes for a ceiling vented enclosure, a first experimental study was conducted for a fully developed wooden crib fire in a reduced scale compartment, at the University of Edinburgh's laboratory. The fire position, fuel loading, vent opening size and vent position were varied to provide a comprehensive account of the behaviour, whilst temperature, vent flow, mass loss and heat release measurements were recorded.

The two main aims of this study were:

- Observe and characterise the different modes of burning for a fully developed compartment fire where the primary opening is in the ceiling.
- Evaluate the controlling physical conditions of the respective modes and identify quantitative correlations to the measured experimental parameters.

Three basic burning modes were identified this first study, specifically: (a) an erratic 'pulsating' diffusion flame (Figure 5.1a), (b) a 'ghost' flame, detached from

[3] The Rimen, 1995 report states that if the pavement light is removed and is seen to be having an adverse effect upon the situation, it may be possible to replace it, or blank it off, disregarding a violent change in the burning behaviour – as a consequence of the venting strategy – which of course would not allow for remediation of a potentially devastating event.

the fuel surface (Figure 5.1b), and (c) an asymmetric burning mode (Figure 5.1c). Having identified this modes of burning, the main aims of the experimental study were to identify the conditions necessary to bring about a transition from one mode of burning to another.

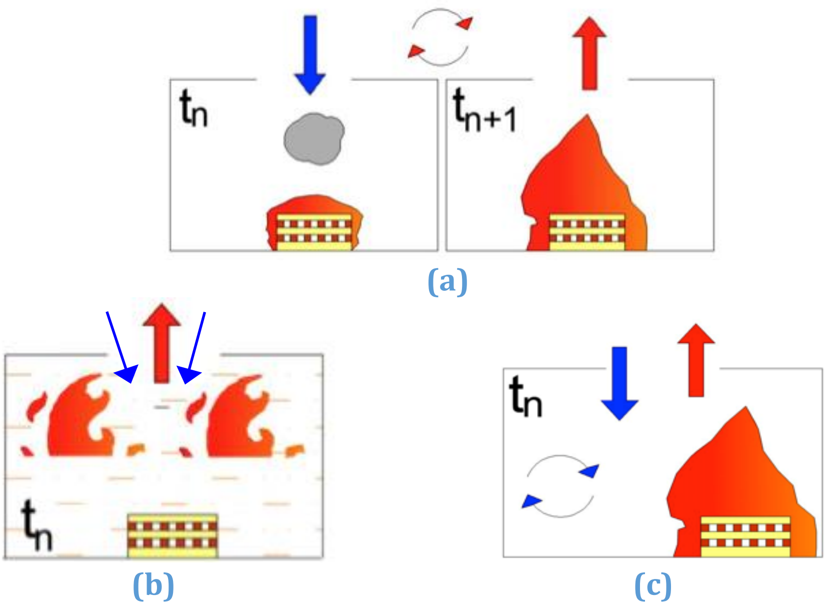

Figure 5.1: Burning Modes: (a) Pulsating Diffusion Flame, (b) Detached Ghost Flame and (c) Asymmetric Burning

5.1.2 Overview of Burning Modes

To offer understanding of the three basic burning modes identified in the experimental study objectives, they are characterised below along with corresponding hypothesised conditions.

5.1.2.1 Pulsating Diffusion Flame

The pulsating or pulsing diffusion flame describes a burning behaviour with an anticipated oscillation between a reduced fire, corresponding to the entrainment of air inward, and a period of large flames, corresponding to the exhaustion of hot gases. As shown in Figure 5.1a, the movement of gases is expected to be predominantly unidirectional with an alternation of a dominant inflow then outflow.

5.1.2.2 Ghost Flame

The ghost flame or ghosting mode is expected to occur under restricted ventilation when the temperature is high, this creates a detached flame which circulates around the compartment (Figure 5.1b). To achieve such conditions, it is anticipated that the prevailing flow across the vent boundary is the outflow of hot gases.

5.1.2.3 Asymmetric Burning

The asymmetric burning mode is anticipated to occur under larger openings where contrary to the other modes, there is a clear segregation between the hot outflow gases and cooler air inflow. Flames are expected to remain attached to the fuel under a classified steady-state mode where the burning behaviour is wholly sustained over time.

The mode is predicted to occur for a non-symmetric fuel loading as shown in Figure 5.1c.

5.1.3 Compartment Configuration

The test compartment was fabricated with inner dimensions of 60cm (W) x 60cm (L) x 40cm (H) as a 1:6 scale model of the enclosure which was used in the BRE/DCLG experimental programme (Figure 5.2). The housing was constructed from 25mm ceramic fibreboard, with all joints sealed using fire cement and taped to minimise air leakage. The compartment also contained an 18cm (W) x 27.5cm (H) glass viewing panel to allow for observation during testing.

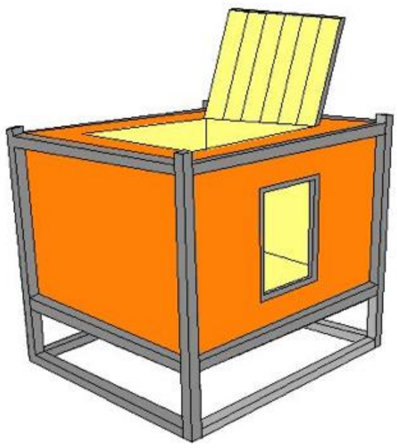

Figure 5.2: Scale Model Test Compartment

The compartment was fitted with an adjustable vertical opening (0-2400cm^2) that conformed to one sidewall to permit flashover conditions to be achieved within the enclosure. The roof consisted of a six-hatch-system that enabled the horizontal opening area and position to be varied. Each hatch measured 20cm x 10cm (200cm^2) allowing the area to be varied from 200cm^2 to 1200cm^2. Figure 5.3 shows the compartment during test set-up.

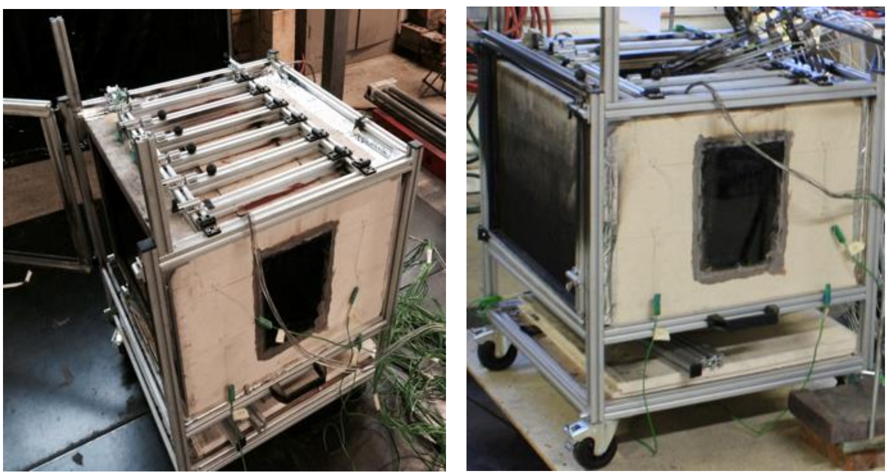

Figure 5.3: Compartment During Test Set-up

5.1.4 Fuel Description

The selected fuel was Scandinavian Spruce softwood arranged as a standard wooden crib, to provide a fast burning fuel source. The baseline fuel loading was a 32-stick fire constructed from 8 layers each consisting of 4 sticks measuring 22.5cm (L) x 3.2cm (W) x 1.6cm (H) (Figure 5.4). To aid ignition and ensure a predominately uniform burning, four 25cm paper rolls were each soaked in 5ml of heptane and positioned within the crib.

Figure 5.4: Baseline Wooden Crib

Two tests were conducted with a fuel loading which was double that of the baseline crib. This involved a 64-stick test with a 16 layer crib and a second alternate approach using sticks of dimensions 45cm (L) x 3.2cm (W) x 1.6cm (H) in a crib the same height as the baseline configuration.

5.1.5 Experimental Procedure

A schematic of the experimental configuration which was used is shown in Figure 5.5. Since it is difficult to identify flashover conditions in a top vented compartment, the variable vertical opening was utilised to establish a fully developed fire and provide repeatable experiment conditions.

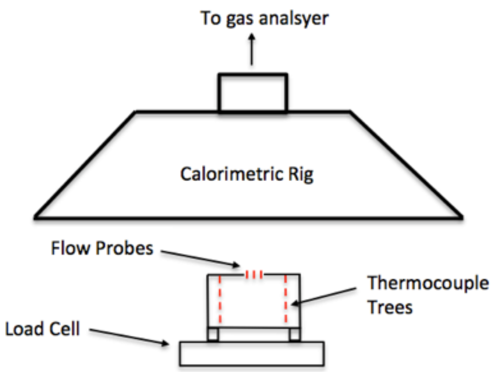

Figure 5.5: Experiment Configuration

After configuring the compartment and performing the necessary preparatory tasks including calibration of measuring equipment, the crib was ignited using a blowtorch for a heating period of approximately 1 minute. The variable vertical opening was then positioned at a height of 15cm from the compartment base, analogous to an opening area of 900cm^2.

Since flashover is a somewhat ill-defined event, a number of both qualitative and quantitative indictors were used in the procedure to ensure a consistent approach. A commonly adopted indicator is the evidence of external flaming from the compartment as a means of representing a ventilation-controlled regime. At this point, the burning of combustible gas within the compartment is limited by the supply of oxygen and as a result unburned gases escape mixing with the ambient air to form a flammable mixture that is subsequently observed to be burning. Whilst this indicator was applied during preliminary testing, it was apparent that due to different fuel positions and fuel quantities, this indicator might be evident at vastly contrasting times with significant differences in compartment temperatures. As a result, for the remainder of testing the quantitative indicator of an upper layer gas temperature tending towards 600°C was sought in addition to the visual observation of external flaming as a means of defining a fully developed fire regime.

At the point flashover was identified, the ceiling hatches were opened to the desired orientation before the vertical opening was entirely closed. In tests measuring flow velocity, the probes were lowered to the plane of the vent during a transitional period of approximately 30 seconds after flashover.

5.1.6 Data Measurement

5.1.6.1 Temperature

Temperatures were recorded in the compartment using four thermocouple trees each with eight semi-rigid K type thermocouples spaced equally over the height of the compartment. The trees were placed towards the corner of the compartment at a position of approximately 10cm from the neighbouring walls.

5.1.6.2 Heat Flux

A series of thin skin calorimeters (TSCs) were embedded into the compartment walls, ceiling and floor and sealed to provide the best possible accuracy in recording a rate of back surface temperature rise.

5.1.6.3 Gas Analysis/ Heat Release Rate

Testing was conducted under a large calorimetric rig that extracted a sample of exhaust gases and passed the flow through a gas analysis console to determine the concentration of oxygen, carbon dioxide and carbon monoxide species. Whilst soot measurements can enhance HRR calculations for incomplete combustion, the required apparatus was not available within the laboratory at the time of testing.

5.1.6.4 Mass Loss Rate

Mass loss was recorded in some tests by placing the compartment onto a load cell. The mass loss rate (MLR) was deduced using the difference between 10-second averages of the recorded mass to provide an appropriate level of smoothing.

5.1.6.5 Pressure and Flow Measurement

Bi-directional flow probes were used to establish a differential pressure across the vent boundary and provide valuable flow velocity measurements. Typically, five probes were positioned along the middle of the opening, spread over the longer axis. A thermocouple was also positioned at the head of each probe to measure the local gas temperature and facilitate a correction of the gas density.

5.1.6.6 Video Footage

Video footage was also taken during each experiment as a means of reviewing the burning behaviour.

5.1.7 Schedule of Testing

A total of twenty-nine tests were carried out for a range of both standard and fire control configurations. Standard experiments were conducted with maintained physical conditions, whilst fire control tests were introduced as a unique addition to this experiments, to replicate realistic strategies employed by the fire service as a means of mitigating a ceiling vented fire. The six ceiling hatches were labelled H-1 to H-6 as shown in Figure 5.6 to allow easy identification of the vents opened for different tests. The positioning of the crib for a wall or corner fire test is also indicated.

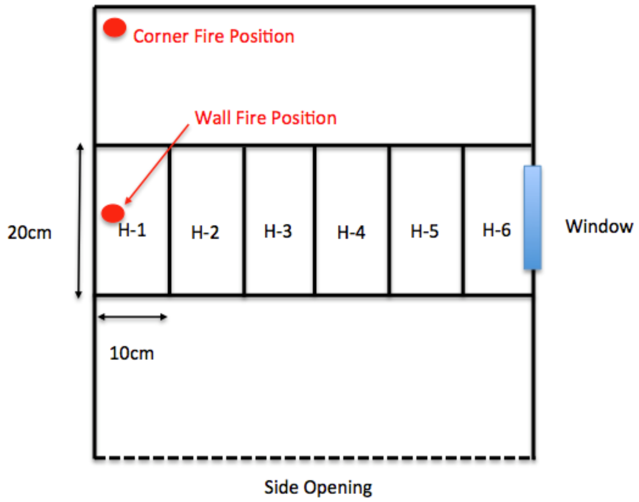

Figure 5.6: Ceiling Hatch Configuration

5.1.7.1 Preliminary Testing

Initially, eight preliminary experiments were conducted to identify a sufficient baseline fuel load to achieve flashover conditions. The tests also offered an indication of the physical conditions corresponding to different burning modes and highlighted areas that could be explored as a focus of the project research.

5.1.7.2 Standard Tests

Upon completion of the preliminary testing, sixteen standard tests were performed to further investigate the observed burning modes and deduce apparent correlations to the test parameters.

5.1.7.3 Fire Control Tests

Whilst increasing the opening area has a more practical use and represents potential mitigation strategies, two tests were performed to investigate the reduction in the opening area.

5.1.8 Results

To present the results in a logical and coherent manner, the standard test data is split into three sections based on the *central*, *wall* and *corner* fire positions. The results for *fire control* tests are subsequently given in a separate section.

To minimise the size of this report, only the main observations are presented here, while the data is left available upon request.

5.1.8.1 Central Fire

The central fire position was the most extensively tested with multiple experiments for different vent opening areas and fuel loadings. The 32-stick fire conducted for two central openings (400cm^2) was the most frequent test and is classified as the baseline condition with the results presented first. The results from varying the time of opening the ceiling hatches and also the fuel load for a 400cm^2 central opening are outlined thereafter. The section is concluded with review of the influence of varying the opening area.

5.1.8.1.1 Baseline Central Fire

For the baseline central fire two tests were conducted under the same conditions and were observed to exhibit a similar burning behaviour with some subtle differences. Shortly after the side-vented fire reached flashover, the top was opened up and the side vent was closed. After 30s or so of erratic behaviour, the fire established itself into a pattern of a period of ghosting flames in the compartment, followed by a surge of flame from the opening, then returning to ghosting, and so on. This is shown in Figure 5.1. Later in the test, the burning in the compartment reduced considerably and a column of white smoke was produced, see Figure 5.2(a). This was followed, some moments later, by a sudden re-ignition like a backdraught, see Figure 5.2(b), and the fire resumed its ghosting behaviour (without the surging), until the fire burned out some minutes later.

(a) (b)

Figure 5.7: Ghosting Mode: (a) Ghosting Within Compartment, (b) Surge of Flames from Opening

(a) (b)

Figure 5.8: Sudden Re-ignition: (a) Column of white smoke, (b) Burst of Flames from Opening

5.1.8.1.2 Variation of Vent Opening Time

To analyse the controlling conditions of the burning modes observed in the baseline central tests, a single experiment was performed where the ceiling hatches were opened prior to reaching a fully-developed fire regime. After a short fire growth period, a 400cm^2 opening was configured prior to reaching flashover conditions. Different to the baseline central fire tests, a small steady-state fire was initially observed within the box, with no flames extending from the opening. Rather than showing a transition to a detached flaming mode, the fire maintained this behaviour before a pulsing diffusion flame was observed, see Figure 5.9. The fire behaviour then transitioned to a detached ghost flame as observed in the later stage of the baseline tests.

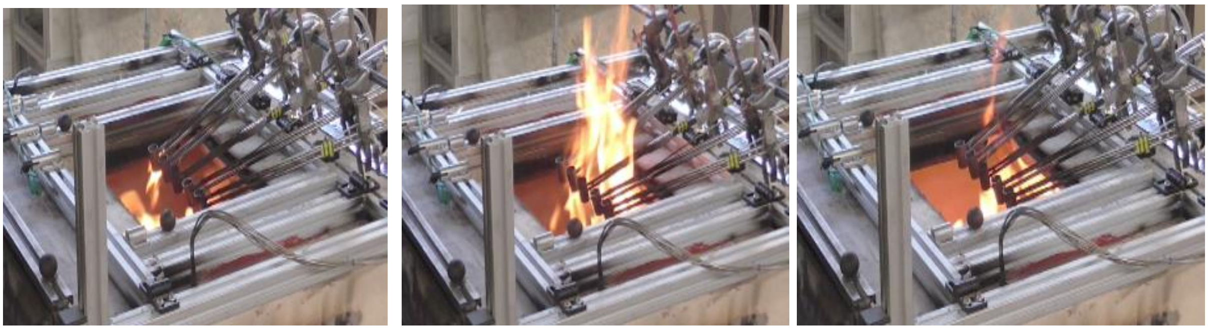

Figure 5.9: Pulsing Diffusion Flame Showing Oscillation of Flames Across Vent Boundary

5.1.8.1.3 Variation of Fuel Loading

Two tests were conducted to review the effect of varying the baseline fuel load. In these tests, since the baseline fuel load was doubled, the burning behaviour appeared to exhibit a possible ‘pool fire’ mode, with the flames resting on a plane just below the vent opening. The ‘pool fire’ mode was theorised as a possible burning mode in the DCLG study, but was not observed. In this mode, the flame totally detaches from the fuel, but the heat generated by the flame at the opening is sufficient to maintain pyrolysis at the fuel location. In our test, burning was sustained at the opening and emitted high levels of heat for a period of over 500 seconds, see Figure 5.10. This behaviour was never observed with lower fuel loadings.

Figure 5.10: Possible Pool Fire Behaviour

5.1.8.1.4 Variation of Vent Opening Area

In addition to the tests conducted for a central vent area of 400cm^2, other tests were performed for 200, 600 and 800cm^2 openings to investigate the correlation between the opening size and fire behaviour.

When the smallest opening of 200cm^2 was used, upon opening the ceiling vent an initial period of white smoke was observed with a sudden large re-ignition in an event similar to a backdraught. The fire behaviour was then dominated by an extreme pulsing mode with an oscillation between an outflow of white smoke and the surging of flames from the opening. The alternation between the events appeared to start with an approximate 10-second frequency, and the short periods of white smoke were followed by small bursts of flames. The behaviour then transitioned to show longer periods of smoke outflow, with a subsequent much larger surge of flames. Burning was then briefly sustained as a detached ghost flame, before returning to an extended period of smoke outflow, see Figure 5.11. The flames had a vivid orange colour and were observed to burn predominately at the opening.

Figure 5.11: Extreme Pulsing Mode- Extended Oscillation Between White Smoke and Ghosting at Opening

Under the largest opening of 800cm^2, the fire behaviour was vastly different to previous observations. After establishing the top vented conditions, the fire maintained an apparent fuel controlled burning regime with large flames extending from the fuel surface out of the horizontal vent. The characteristics of the fire were indicative of an asymmetric burning mode with flaming concentrated on the window side of the compartment, see Figure 5.12. This fire never exhibited under-ventilated behaviour.

Figure 5.12: Asymmetric Burning Mode

5.1.8.2 Wall Fire

Three tests were conducted for a wall fire position and all used the baseline 32-stick fire. The results for a 400cm^2 central opening are presented first as the baseline condition, before the influence of varying the vent position and opening area are introduced.

5.1.8.2.1 Baseline Wall Fire

With the fire positioned at the side of the compartment and a 400cm^2 central opening, the burning behaviour showed initial evidence of a detached ghost flame, concentrated on the side of the box the fuel was positioned (Figure 5.13). The flame appeared fainter than that observed for a central fire test with a 400cm^2 opening. After a ghosting period, the fire changed to show flaming in an apparent asymmetric mode with yellow flames impinging on the vent opening, whilst extending from around the fuel surface (Figure 5.14). Finally, the fire reduced to a low-flaming, steady-state mode before reaching extinction.

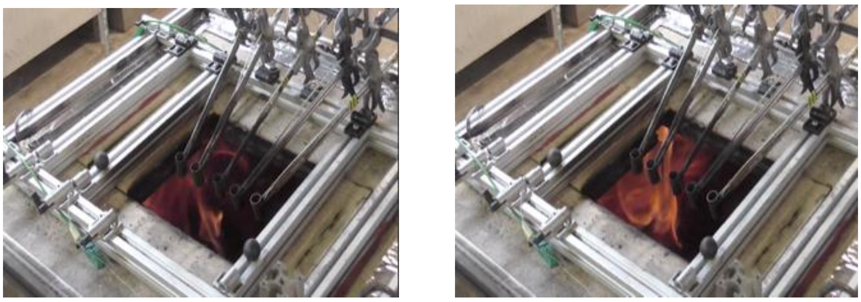

Figure 5.13: Concentrated Detached Ghosting

Figure 5.14: Apparent Asymmetric Burning

5.1.8.3 Corner Fire

A single test was conducted with a central 400cm^2 opening to investigate the influence of positioning the fuel in the corner of the compartment with two adjacent boundary walls.

When the ceiling flaps were opened the fire behaviour transitioned to a detached ghost flame behaviour which was concentrated in the fuel corner, with little flaming observed in the rest of the box (Figure 5.15a). The burning appeared to be focused around the base of the crib and had a tendency to lick along the ceiling occasionally surging from the opening. Whilst not the same as the ghosting behaviour observed in the earlier central or wall fire tests, the detached flaming away from the fuel surface indicated that the fire was not in a simple fuel controlled regime. After burning for a period, the flames reduced to a small pocket of flames above the fuel before tending to extinction (Figure 5.15b).

(a) (b)

Figure 5.15: Ghosting Behaviour: (a) Detached Flaming around Crib Base, (b) Pocket of Ghost Flames Above Crib

5.1.8.4 Fire Control

Five experiments were conducted with the ceiling opening varied during the test, to represent potential fire control strategies for both a central and wall fire position. As a more realistic approach, experiments where the opening area was increased are given first, and trials using a reduced opening area are provided thereafter.

Two tests were conducted for a central fire position with an increase in the opening area, to investigate how the compartment temperature responded with the fire changing from a ghosting behaviour to a fuel controlled asymmetric mode. One test was performed using a transition from a central 2-hatch opening (400cm^2) to a central 4-hatch opening (800cm^2). Showing similar behaviour to the baseline test, there was an initial prolonged exhaustion of white smoke that commenced a few seconds after configuring the 400cm^2 opening. Due to the unpredictability of the following sudden re-ignition event, the additional two hatches were not opened until after the rapid deflagration to maintain a safe experiment procedure. Whilst the mode transitioned from ghosting to asymmetric after increasing the opening to 800cm^2, no distinct difference in the temperature profile was evident relative to the observations from the baseline test. This was most likely a combined result of a depleted fuel source, and the post re-ignition temperature profile masking the apparent change.

A single test was performed for a wall fire position with a transition to a larger opening, to enable a comparison to the observed trend for the central fire experiments. The behaviour was largely the same as above.

As a result of the unpredictable rapid deflagration event evident for central fire conditions, two fire control tests were conducted using a reduction in the opening area. This ensured a safe experiment procedure whilst providing valuable information on the ways in which the fire behaviour and temperature varied under differing opening conditions. Initially, large flames were observed to reach out of the box at the side opposing the window, with a strong level of heat emitted from the fire. After two of the hatches were closed, the fire immediately transitioned to an erratic ghosting mode with detached flaming. The flames had a strong orange colour similar to the observations above, and brief puffs of faint white smoke were evident. However, the smoke outflow was not sustained for any significant period. After a while, the ghosting became less pronounced and the flames circulated around the compartment without evidence of surging from the opening.

5.1.9 Conclusions for WP1

The different burning modes of a fully-developed fire in a ceiling vented compartment have been investigated by conducting a series of experimental tests using a reduced scale (cubic) apparatus. In addition to evaluating the controlling physical conditions of the respective modes, quantitative correlations have been identified to the measured experimental parameters. A wooden crib fuel source was used for a varied fire position, fuel load, vent opening size and vent location, to provide a comprehensive study of the fire behaviour.

The following conclusions have been identified for the three burning modes outlined in the first experimental phase's objectives:

1. A detached ghost flame has a tendency to occur under a restricted vent opening where the upper layer temperature exceeds 450°C. It is categorised as a ventilation-controlled behaviour with a

predominately unidirectional outflow resulting from a large pressure force, generated by the elevated compartment temperature. There is no region of maintained inflow and the fire behaviour is sustained under oxygen lean conditions, supported by oscillating low velocity inflow. The behaviour was observed where a central opening was less than 17% of the roof area for a central fire position, and smaller than 11% for a wall fire position. Whilst recorded upper temperatures fluctuated between 450 and 650°C, it is anticipated due to the constrained oxygen inflow there should be a level of uniformity across the upper plane and over the test duration. This was not observed due to a possible poor seal at the enclosure joints. Gases are well mixed with no evidence of distinct layers and temperature over the compartment height varies linearly with a consistently recorded heat flux. Average mass loss rate and heat release rate were observed between 0.75-1.15g/s and 9.2-14kW respectively, with higher values under larger opening areas and a central fire position.

2. A pulsing diffusion flame occurs at a lower temperature of between 400-500°C and exists as an unstable transitional regime. The behaviour appears as the buoyancy dominated bidirectional flow is overcome by a more dominant pressure force, however a larger low velocity inflow is achieved than in ghosting. This means sufficient inflow permits the flames to remain attached to the fuel surface. Temperatures tend to be uniform across a plane and vary linearly over the height with a discrepancy of around 130°C. With a lower compartment temperature, mass loss rate and heat release rate are less than in a ghosting regime.

3. An asymmetric burning mode will form under larger ventilation openings, observed in this research to be more than 22% and 17% of the ceiling area, for a central and wall fire respectively. The vent flow is a buoyancy dominated regime with a stable bidirectional flow providing a plentiful supply of oxygen in a fuel-controlled regime. Temperatures are hotter than in a ghosting mode and vary over the test duration following a bell shaped profile with potential for high localised temperatures exceeding 750°C. A clear discrepancy exists between the compartment sides due to the balanced flow nature, with a central fire recording a consistent difference of 100°C. On the hotter compartment a staggered temperature variation exists over the height, with a 200°C discrepancy resulting from the large flames. Mass loss rate and heat release rate will be higher than in a ghosting regime as the fire burns constrained by the characteristics of the fuel.

In addition to the three key modes identified in these experiments, a series of adapted behaviours were observed that can be categorised as follows:

4. Under a central fire position with a 400cm^2 opening, an erratic ghosting behaviour was evident where detached flames intermittently surged from the opening. This was identified as a combination of the ghosting mode and a pulsing effect caused by the oscillation of low

velocity flow. Where a large pressure difference exists across the boundary, a rapid re-ignition event analogous to a backdraught may also occur. This is a highly unpredictable behaviour which can have a varied duration depending on the prevalence of an ignition source.

5. An extreme pulsing behaviour may occur as an amplified example of the erratic ghosting mode if the vent opening is very small (<6% ceiling area). Under such conditions it is difficult to sustain flaming within the enclosure and the fire oscillates between a venting of white smoke and a ghosting behaviour surging from the opening. Upper temperatures are lower than ghosting at between 400 and 500°C with lower layer temperatures remaining largely constant throughout. From the tests conducted, the event appeared with an initial 10-second frequency before reducing to around 40 seconds.

6. A pool fire behaviour with maintained burning at the vent opening can occur under large fuel loadings where there is a sufficient supply of volatiles. Temperatures are uniform over a horizontal plane and upper layer measurements will approach 700°C. There is no evidence of layers over the compartment height with a consistent heat flux of between 1 to 1.5kW/m^2. Heat release rate and mass loss rate are much greater than a ghosting regime as burning at the opening is not constrained by air inflow.

Further to identifying the characteristics of the controlling burning modes, a series of correlations between the experimental data and varied physical conditions were deduced:

7. A larger vent opening area provides hotter average upper layer temperatures under a central fire position. This is concurrent with an increase in the mass loss and heat release rate and can be attributed to the greater supply of oxygen. Under ventilation controlled conditions there is an apparent proportionality between the opening area and the recorded MLR and HRR. A transition to a fuel controlled behaviour was observed for an opening area 22% of the ceiling area, where this relationship broke down.

8. The vent shape in addition to the area may influence the controlling flow conditions. Under a rectangular shape a more efficient flow exchange may exist which can allow a bidirectional flow to be established for a smaller area than a symmetrical square vent.

9. A wall fire or corner fire in a ventilation controlled regime has localised flaming that creates an imbalance in between a hotter and a cooler side. In a fuel controlled mode the temperature imbalance of an asymmetric behaviour is exaggerated relative to a central fire position.

10. An eccentric fire position has a more efficient flow across the vent boundary with a smaller pressure difference. This creates less

dangerous conditions than when the fire exists directly below the vent, where erratic ghosting or a rapid re-ignition event may occur. A balanced bidirectional flow can develop for a vent size 17% of the ceiling area under a wall fire position, whilst a larger vent, 22% of the roof area, is required for a central fire.

11. Despite a more efficient vent flow, a fire against a wall has a restricted air exchange, which decreases the MLR and HRR compared to a fire in the same burning regime positioned in the compartment centre. The reduction appeared to be 10-15% for the wall fire, and around 25% for the corner fire.

5.2 WP2 Outcome

5.2.1 UK

Several UK based fire brigades where contacted not only to understand and discuss what their operational procedures and techniques currently are regarding tackling basement fires situations (i.e. WP2), but also to develop a collaborative relationship between them and the BRE Centre for Fire Safety Engineering at the University of Edinburgh for this (i.e. for the next two phases: WP3 and WP4) and future projects with similar practical application.

Two of the brigades contacted were very positive about the project and the interaction – LFB (London Fire Brigade) and SFRS (Scottish Fire and Rescue Service) – thus, it was decided to concentrate all the efforts and resources along these two paths.

The following is a summary of their current approaches to fire-fighting in basements and consequent operational procedures:

5.2.1.1 SFRS

SFRS considers that the venting of basements using pavement lights cannot be relied on as a safe practice. This relies on the fact that successful venting during a fire is too dependent on wind and pressure conditions at the vent outlet and identification of the correct vent to operate.

In a similar way, SFRS considers that venting of a basement compartment via a second compartment is not a safe practice to use during fire-fighting.

Therefore, SFRS recommends to use standard compartment entry tactics as described in their Fire Service Manual, keeping venting to a minimum, and avoiding the use of natural vents from basements until full extinguishment of the fire is confirmed or extinguishing media are ready for immediate use to control any possible fire development.

As part of SFRS on-going development of an operational guidance framework, consideration is continually given to the revision of the existing guidance in the Fire Service Manual to address issues like this one.

5.2.1.2 LFB

With a similar approach to SFRS, LFB explicitly acknowledges – in their relevant policy procedure – the fact that the incorrect use of ventilation systems may adversely affect any persons involved in the fire situation, resulting in rapid or uncontrolled fire spread, and possibly leading to backdraught conditions.

The following is a bullet summary of their procedure in regards to venting:

- Ventilation of basements should only be carried out under strict supervision and only on the order of the IC (Incident Commander).
- Prior to ventilation taking place, covering jets adjacent to any openings where the products of combustion are likely to escape, must be in position.
- If practicable and when the immediate rescue of persons is not required, ventilation of the basement should take place prior to committing BA teams in order to provide a safer working environment.
- Ventilation has the potential to improve working and escape conditions at basement incidents, but before a decision is made to ventilate a basement, consideration must be given to its impact on rescues at any 'persons reported' incident.
- Under no circumstances should a basement or any other part of the premises that may affect the basement, be ventilated whilst BA teams are committed. This is because the influx of oxygen may lead to rapid fire spread and possible backdraught conditions.
- When automatic mechanical ventilation systems are fitted their effects on prevailing conditions and fire and smoke spread should be monitored.

5.2.2 Europe

A few other fire brigades from continental Europe were contacted to discuss their approach to fighting fires in basements, and allow for comparison to what is done in the UK.

5.2.2.1 Norway

Based on discussions[4] with fire fire-fighters in Norway the most common practice of fire fighting in basement is to let the ventilation go naturally and eventually use PPV (Positive Pressure Ventilation) at the entry door, only if there is an opening like a window on the wall opposite the entry door opening.

[4] Discussions led by Jan Smolka as part of his 'Fires in Underground Spaces' project at the University of Edinburgh (2015)

5.2.2.2 Sweden

In Sweden, because the government contributes to building domestic shelters, there is typically a large number of basements which in non-emergency situations have different uses. This, added to the fact that the north of the country has a very low population density and that therefore the Fire Stations are quite remotely located, means that it takes longer for the Fire Brigade to arrive to the scene, where they will typically find the fire in a fully-developed stage.

For these cases, the Swedish brigades usually approach the extinguishing externally with FogNail Nozzles or Cobra Cold Cut Systems which tend to reduce the threat for fire-fighters.

5.2.2.3 Czech Republic

Similarly to the Norwegian case, in the Czech Republic the most common practice of fire fighting in basement is to let the ventilation go naturally and eventually use either PPV (Positive Pressure Ventilation) or NPV (Negative Pressure Ventilation) at the entry door, only if there is an opening on the wall opposite the entry door opening.

5.2.3 Summary of Approaches Discussed

It is apparent from these summarised and simple descriptions of the different approaches in the UK and Europe that none of them are keen to force a sudden ventilation situation (e.g. by breaking an opening), but rather eventually enhance the naturally established compartment ventilation pattern. This is to avoid rapid changes in the ventilation and/or burning mode, which could lead to violent changes in the burning behaviour.

5.2.4 Development of a collaborative relationship with UK Fire Brigades

As stated above, the aim of this Work Package (WP2) was not only to understand and discuss current operational procedures and techniques with different fire brigades, but also to develop a collaborative relationship between them and the BRE Centre for Fire Safety Engineering with immediate focus on the next two phases (WP3 and WP4) of this particular project, and long term focus on future projects with similar practical application.

The results of this engagements during the project are the following:

5.2.4.1 SFRS

5.2.4.1.1 Christie Commission - Project Background and Description.

Within the public sector there is a significant shift in how, where and when it provides its services. The Scottish Fire and Rescue Service (SFRS) needs to be viewed as an integral part of the public sector family and the move to a national fire and rescue service for Scotland has provided the opportunity to reconsider the approaches taken by the previous eight service arrangement.

New mind-sets need to be established within SFRS that will ensure the strengths of the Service are protected but at the same time move the organisation forward to ensure there is a clear picture of the contribution it makes; how the culture of the organisation is reformed to suit the new public service paradigm and how it captures the needs and aspirations of communities across the diverse Scottish geography. The binding force that brings all parts of the public sector together during this significant period of change is the Commission on the Future Delivery of Public Service.

The Christie Commission sets out the principles for reform of Scotland's public services.

5.2.4.1.2 Christie Commission - Our task

We have been invited to help SFRS accomplish the mission of efficiently employing their resources to contribute to the collective capacity of the public, private and third sectors in managing risk in all communities.

In practical terms, our immediate task is to help SFRS assess the general fire risk in pilot communities, evaluate the different mitigation alternatives, and help shape an optimised coverage and response to potential emergency events.

5.2.4.1.3 New (2016) Research Project

As with the LFB, see above, the SFRS was also invited to join on the new proposal submitted by the University of Edinburgh to, and approved and funded by, the FSRTT: "Effectiveness of the *gas cooling technique* in larger compartment fires"[5]. The new project is directly related to – and will be carried out immediately following completion of – the present project subject of this report, also funded by FSRTT. This will substantially enhance the future project, as the same University of Edinburgh staff and resources is allocated to it.

The SFRS agreed to support and participate in this project through a formal letter of support, and invited us to their training facilities at Thornton, Fife, to formalise and kick-off the cooperation in this regard. We attended the training facilities in early February 2016 and experienced a demonstration of the current *gas cooling technique* (or *safety fire-fighting technique*) in their large-scale flashover container.

This new research project is intended to assist in determining the current effectiveness of entry into, and fire-fighting within, large compartment fires. The outcome of the research will support amendments to current procedures and techniques should they be required and assist in improving fire-fighter safety.

[5] Note: The proposal was originally titled "Effectiveness of the safety fire-fighting technique in larger compartment fires", but during the initial stages of this project it was established that "gas cooling technique" is the more appropriate terminology, so this phrasing will be used forthwith.

5.2.4.2 LFB

Along the project, we have meet, discussed and agreed to help open a double-way educational dialogue between the BRE Centre for Fire Safety and LFB. The aim was to give fire-fighters some real underpinning knowledge and practical vocabulary for putting the knowledge into actions.

In particular and as a first task, we were invited to provide LFB with scientific feedback on their *Tactical Ventilation* Policy Note which is was being reassessed to produce a new revision. Our feedback was submitted, and the draft Policy was prepared for review by internal departments in London, awaiting to see it published in the near future. These practical guidelines have the potential to be mirrored among the different fire brigades in the UK – and probably beyond – very quickly. LFB acknowledged the fact that we gave feedback on their draft document.

After the positive results and favourable outcome attained during the first task, the second step agreed was to broaden the objective of this specific basement project by focusing on general ventilation issues and beyond. All our efforts were directed to lay the basis to develop, review and disseminate further LFB's Policy Notes in the future, with the fundamental concepts beneath the proposed tactics explained in an elementary and strongly didactic style. A briefing document was shaped and put forward to the Senior Officers at LFB to formalise this cooperation.

5.2.4.2.1 New (2016) Research Project

As with the SFRS, the LFB was also invited to join on the new proposal submitted by the University of Edinburgh to, and approved and funded by, the FSRTT: "Effectiveness of the *gas cooling technique* in larger compartment fires".

5.3 WP3 OUTCOME

In regards to this phase, a larger-scale (elongated) apparatus, containing two 'rooms', was built and utilized to investigate fire behaviour in a more realistic (basement-like) geometry. Different configurations were tested where forced rapid changes in the ventilation conditions produced violent changes in the burning behaviour.

BRE, LFB, and the SRFS were invited to participate in this experimental phase, in an effort – and as part of the formal task – to feed the double-way educational dialogue with the UK fire brigades mentioned and described above. A document titled "*Experimental Design & Setup for WP3*" was sent for their feedback, which was taken into account in the final standardised procedure.

5.3.1 Aims & Objectives

The combination of opened and closed doors and ceiling vents during the experiments were thought to simulate the basic conditions during a typical basement fire. Once certain conditions were attained, the openings were varied to trigger extreme fire behaviours and phenomena, more specifically, flashover and backdraught.

The general aim was to reveal which were the main conditions that triggered the flashover and backdraught extreme fire behaviours, monitor these from a fire-fighting perspective to recognise practical thresholds and imminent backdraught situations, and take practical actions to minimize or ideally avoid such extreme phenomena.

In this experimental setting (described below), it was found that using polypropylene (PP) pellets as fuel load, the combination of opening 'door 1' and 'door 2' consistently forced 'room 2' in the apparatus to a **flashover**. This was recognised by the following events:

- Average temperature in 'room 2' was > 650°C
- Average temperature in 'room 1' was > 250°C
- Smoke layer in 'room 2' was visibly combustible, i.e. flames could be seen within and along the hot gas layer
- Flames extended externally throughout 'door 2'
- Flames tended to extend beyond the sill that separates 'room 1' from 'room 2'
- A wooden ember placed on the floor of 'room 2' was completely charred, releasing abundant white smoke, and eventually ignited.

In a similar way, the following minimum threshold average temperatures were recognised as those triggering auto re-ignition and a **backdraught** through either opening:

- Average minimum temperature in 'room 2' during the post-flashover state (immediately before closing all vents) > 700°C
- Average minimum temperature in 'room 1' above the fuel bed immediately before opening a vent > 350°C

In summary,

- The ***first*** experimental package was designed to fulfil the aforementioned aim of revealing which were the main conditions that triggered the flashover and backdraught extreme fire behaviours.

- The ***second*** and final experimental package was designed with the intent of fulfilling the aim of finding practical actions from the fire-fighting perspective that could minimize or ideally avoid a backdraught in a scenario which has previously (and consistently during the first experimental package) shown that it would occur provided no different actions were taken.

5.3.2 Compartment Configuration

An elongated compartment with inner dimensions of 660 mm (W) x 450 mm (H) x 990 mm (L) and various ventilation openings was designed and built at the University of Edinburgh laboratory[6], with the intent of simulating the basic conditions in a typical basement layout configuration, see Figure 5.16. The compartment structure was built using an inner steel frame 50 x 25 mm in profile, while the housing was constructed from expanded vermiculite boards 25 mm thick fastened by an outer aluminium frame 45 x 45 mm in profile to ensure resistance to pressure changes during the experiments. The compartment also contains a 300mm (H) x 400 mm (W) stove glass viewing panel to allow for observation during testing.

For modelling purposes[7], the maximum working temperature for the expanded vermiculite boards is 1100°C; the specific heat is 0.94 kJ/(kg.K), the bulk density is 700 kg/m^3, the thermal conductivity at 600°C is 0.21 W/(m.K).

The compartment is fitted with two vertical openings (i.e. doors) and one horizontal opening (i.e. a ceiling vent) which can be combined opened or closed to trigger different ventilation modes. They have the following dimensions:

Door 1: 100 mm (H) x 400 mm (W)
Door 2: 180 mm (H) x 180 mm (W)
Vent 1: 280 mm (W) x 410 mm (L)

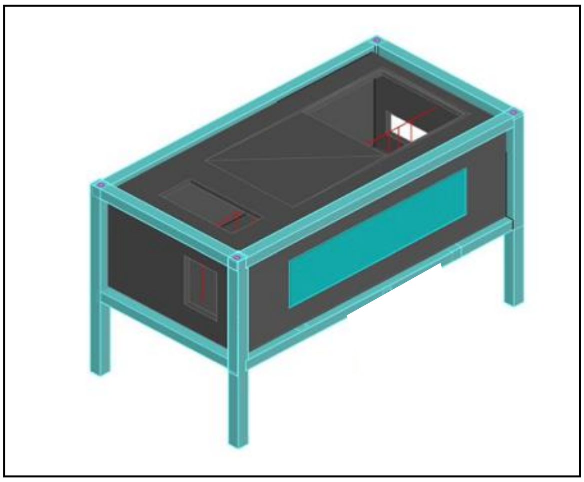


Figure 5.16: Schematic and photo of the small scale apparatus being used in the current "basement fire" study funded by the FSRTT

5.3.3 Fuel Description

Two basic fire loads were tested in this experiments:

- Polypropylene (PP) pellets combined with n-Heptane
- Wood cribs

[6] Jan Smolka 'Fires in Underground Spaces', Master Thesis, University of Edinburgh, 2015
[7] Modelling of these tests is being carried out at BRE by staff on their graduate training scheme. This work is beyond the scope and timescale of the current project, but the eventual results may prove useful.

The final selection of PP pellets as the experimental fuel was based on ease of handling and setup, considering that the latter – in combination with the experimental setup – consistently triggered extreme fire behaviours, obtaining a robust repeatability for comparison and analysis.

5.3.3.1 Standardised fuel load

The optimum ratio of PP pellets to n-heptane was found to be 2:1, and the minimum quantity to trigger flashover followed by backdraught with this fuel combination was found to be 400 g and 200 ml, respectively. The n-heptane was only used to establish the fire; after it were consumed, the fuel load remained as pure PP pellets.

Under all fuel loads, a wooden ember was placed on room 2's floor as a means to recognise when flashover was about to occur (refer to the experimental procedure below). This wooden ember was assumed not to contribute to the overall fire load given its relatively insignificant mass.

5.3.4 Experimental Procedure

As previously stated, the ***first*** experimental package was designed to fulfil the aim of revealing which are the main conditions that trigger the flashover and backdraught extreme fire behaviours. To this extent, the setup was adjusted until a backdraught could be consistently triggered using one or both of the selected (vent 1 & door 2) openings.

The sequence of events to trigger this extreme behaviour repeatedly was found to be the following:

1. Once the flashover conditions have been clearly reached and the compartment evolved to a fully-developed or post-flashover fire, both door 1 and door 2 are fully closed 'killing' the fire. After 120 seconds, vent 1 is opened (50%) to trigger a backdraught through the ceiling opening.
2. A few seconds after the backdraught through the ceiling vent has occurred, door 2 is re-opened (100%) to allow the fire grow again to its peak.
3. Once the fire has evolved to its peak, both door 2 and vent 1 are fully closed 'killing' the fire once more. After 120 seconds, door 2 is re-opened (100%) to trigger a backdraught through the front door opening.
4. A few seconds after the backdraught through the front door has occurred, vent 1 (50%) and door 1 (100%) are re-opened until the remnant of the fuel is consumed and the compartment cools down to ambient temperature.

Also explained above, the ***second*** and last experimental package was designed with the intent of fulfilling the aim of finding practical actions from the fire-fighting perspective that could minimize or ideally avoid a backdraught in a scenario which has previously (and consistently during the first experimental package) shown that it would occur provided no different actions were taken.

The sequence of events to test a practical solution to avoid the extreme behaviour of a backdraught was planned as follows:

1. Once the flashover conditions have been clearly reached and the compartment evolved to a fully-developed or post-flashover fire, both door 1 and door 2 were fully closed ‘killing’ the fire. After 120 seconds, vent 1 was opened (50%) providing the ‘ideal’ conditions that would trigger a backdraught through the ceiling opening.
2. A few seconds (~5) after the ceiling vent was opened (50%), door 2 was re-opened (100%) to allow for a clear double-opening venting path for the hot combustible gases to flow across.
3. The flow direction of the hot gases was assessed (i.e. the flow’s input and output openings recorded).
4. If re-ignition occurred (this was recorded) and if it produced an immediate backdraught as a consequence, the backdraught’s output direction (or opening) was recorded.
5. If re-ignition had occurred, the fire was left to evolve to its peak, and once these conditions were reached, both door 2 and vent 1 were fully closed again ‘killing’ the fire once more. After 120 seconds, door 2 was re-opened (100%) providing the ‘ideal’ conditions that would trigger a backdraught through the front door opening.
6. A few seconds (~5) after the front door was opened (100%), vent 1 was re-opened (50%) to allow for a clear double-opening venting path for the hot combustible gases to flow across, and steps 3 and 4 were repeated.
7. Finally, vent 1 (50%), door 1 (100%), and door 2 (100%) were re-opened until the remnant (if any) of the fuel was consumed (if re-ignited) and the compartment cooled down to ambient temperature.

5.3.5 Data Measurement

In order to investigate extreme fire behaviours and capture the triggering conditions in a practical way – i.e., from a fire-fighting perspective – the gas temperatures within the experimental compartment and the pressure difference through the ceiling vent (Vent 1), simulating a pavement light, and the front door (Door 2), simulating the fire room door, were recorded.

The temperatures were recorded using three vertical thermocouple trees located at different positions within the compartment (see Figure 5.17), each with four K-type thermocouples at different heights.

Two bi-directional flow probes recorded the differential pressure and provide flow velocity measurements across the ceiling vent (Vent 1) and front door (Door 2) boundaries. These probes can capture both inflow and outflow without adjustment, and offer an angular insensitivity of up to 50 degrees which allows placement directly on the plane of the vent.

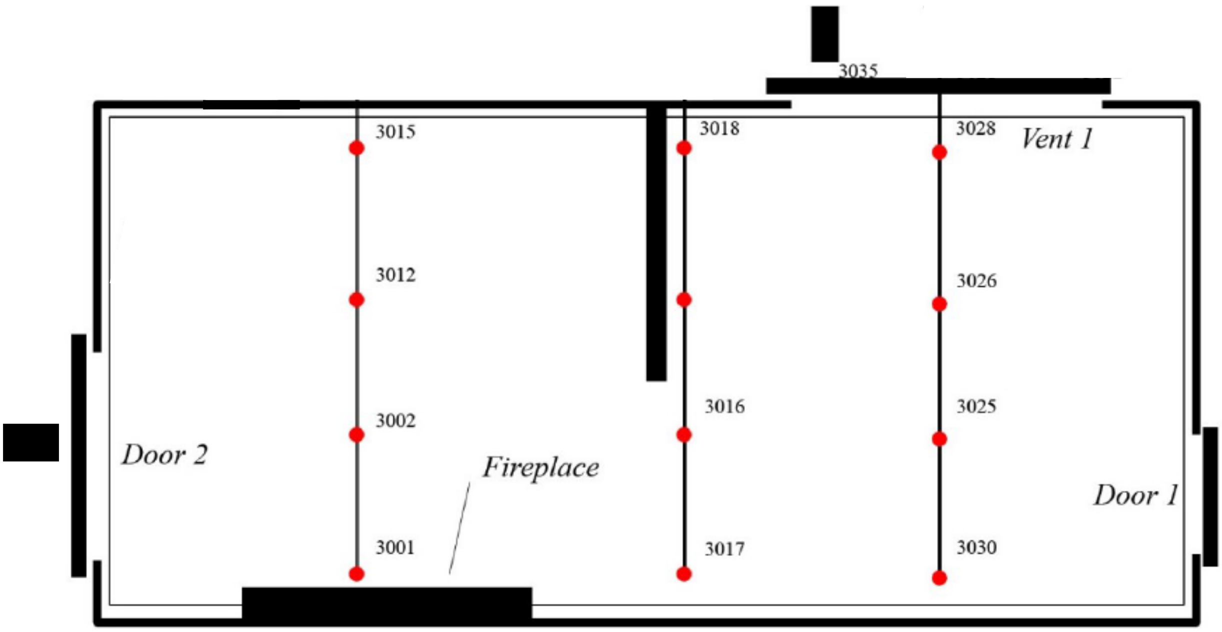

Figure 5.17: Compartment Side View Showing Thermocouple and Pressure Probe Layout. The room to the right is Room 1 (or Smoke Room), while the room to the left is Room 2 (or Fire Room)

5.3.6 Schedule of Testing

The experiments were carried out during November and December 2015, and January and February 2016.

5.3.7 Experimental Results

This subsection summarises the results from the ***first*** and ***second*** experimental packages. The full experimental results are available upon requirement.

5.3.7.1 First Experimental Package

As explained previously (section 5.3.4), in the ***first*** experimental package the setup was adjusted until it consistently triggered a backdraught through either of the selected openings (vent 1 or door 2). The following two graphs show the evolution of the gas temperatures in each room – referred to as *fire room* and *smoke room*, respectively – as recorded by the three thermocouples *trees* (refer to Figure 5.17 for nomenclature), in one of these typical experimental runs.

The relevant sequence of events is highlighted in the graphs themselves:

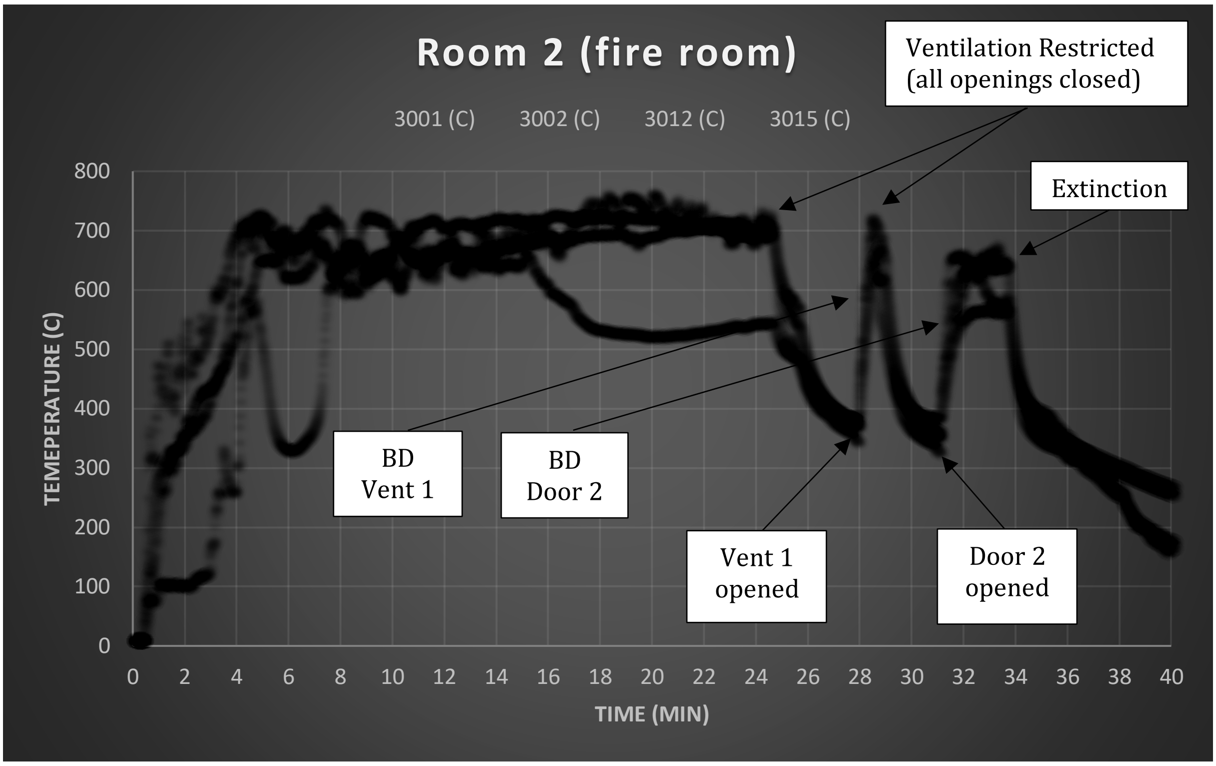

Figure 5.18: Fire Room instant gas temperatures at different height locations ("PP6 Run")

BD Vent 1

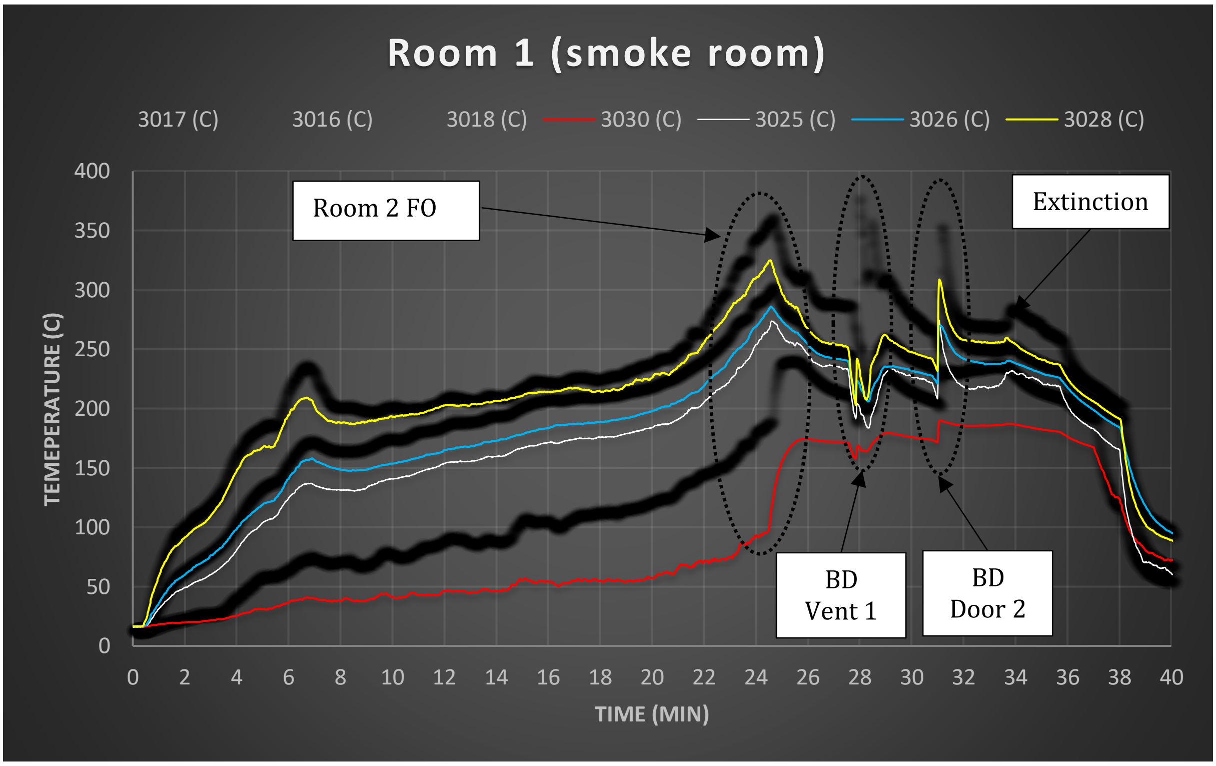

Figure 5.19: Smoke Room instant gas temperatures at different height locations (PP6 Run)

The temperature profiles in each run were very much alike. Once flashover had occurred in Room 2 and the compartment evolved to a fully-developed fire evidenced by a sudden rise in temperature in Room 1, all the openings were fully closed. This is evidenced by the rapid descent of the temperatures in both compartments, revealing a 'dying' fire. After a few minutes, either vent 1 or door 2 (in this sequence order) were opened; this has shown to systematically trigger a backdraught a few seconds after – ranging from 7 to 60s – through the single opened vent or door at that time, as can clearly be seen in the steep temperature increases in both compartments, reaching its peak temperature again; i.e. that attained by the gases (as recorded at different heights) during the fully-developed phase.

The following photos (Figures 5.20 and 5.21) show the violence of the backdraughts triggered through both openings. Figure 5.20 (a) and (b) shows backdraughts prompted through the ceiling vent (vent 1):

Figure 5.20 (a): Backdraught through the ceiling vent (PP10 Run) --- (b): Backdraught through the ceiling vent (PP6 Run)

Figure 5.21 shows backdraughts prompted through the back door (door 2):

Figure 5.21 (a): Backdraught through door 2 (PP8 Run) (b): Backdraught through door 2 (PP10 Run)

The violence of these backdraught explosions can be appreciated after the flames extended externally reaching a length the same order of magnitude as the internal characteristic length of the compartment. This is to say, the vertical backdraughts (i.e. those set off through the ceiling vent) extended externally as much as the compartment height (and even beyond 450 mm), while the horizontal backdraughts (i.e. those set off through the back door) extended horizontally as much as the compartments depth (~990 mm).

The extreme behaviour of a backdraught clearly arises after a substantial pressure build-up, which is a direct consequence of the sudden expansion of the unburnt gases stored within the compartment immediately after igniting. The ignition of the bulk of combustible gases can be triggered by a hot surface like a glowing ember or even auto-ignite if sufficiently hot, proving the high potential of occurrence in compartments undergoing a poorly ventilated fire.

5.3.7.2 Second Experimental Package

It is due to the relevance of the pressure build-up as ultimately appearing to be the main cause affecting the backdraught's severity, that the ***second*** experimental package was designed with the intent of reducing or ideally avoiding such build-up in a practical way from the fire-fighting perspective, and in a scenario which has consistently shown that a backdraught would occur provided no actions were taken.

To this extent, the sequence of events to test a potential practical solution was planned so that almost immediately (a few seconds) after one of the vents was opened providing the 'ideal' conditions that would trigger a backdraught through it, the other vent was opened to allow for an effective clearance of the combustible gases flowing across a 2-opposite-openings venting path, minimising the likelihood and/or severity of a backdraught otherwise violently caused by opening a single vent. This solution is based on the combination of vertical (or top) and horizontal (or cross) ventilation tactics, which rely on the buoyancy of the hot gases and wind (if any), respectively.

An edited video (including several experimental runs' clips) showing the severity of a backdraught through a single ventilation opening, and comparing the same scenario after allowing for a natural (i.e. not assisted by mechanical means) cross flow through two opposite ventilation openings is provided with this report through the following private web-link: https://youtu.be/0Q1YYWGFpIU.

The last two clips show the effectiveness of the natural cross flow through two opposite ventilation openings in minimizing the likelihood (PP7 Ceiling BD) and severity (PP12 TRIAL 2).

PP7 Ceiling BD shows how, after a backdraught through the ceiling vent has occurred and the conditions were evolving towards an imminent second backdraught through it again, opening a second vent (door 2) which promoted a natural cross flow across and away the compartment, the pressure build-up within the compartment was minimised after re-ignition. In sum, an imminent backdraught through the ceiling vent was avoided by opening the back door.

Table 1: Backdraught Videos

Experimental run clip included in edited video	Brief Description
PP6 Ceiling BD	Ceiling backdraught
PP10 Ceiling BD	Ceiling backdraught
PP7 Door BD	Back door backdraught outlook
PP6 Door BD	Back door backdraught from an angle
PP8 Door BD	Back door backdraught close-up
PP10 Door BD 2	Back door backdraught in slow-motion
PP7 Ceiling BD	Ceiling backdraught and subsequent re-ignition after a double ventilation opening
PP12 TRIAL 2	Double ventilation opening significantly reducing backdraught severity

Similarly, PP12 TRIAL 2 shows how opening a second vent – in this case the ceiling vent – minimises the severity of an otherwise evident violent backdraught which would have hit through the back door. In summary, an imminent backdraught through the back door can be avoided or significantly relieved by opening the ceiling vent.

The following snap-shots show the exact instant when re-ignition of the unburnt gases within the compartment occurred:

Figure 5.22 (a): Flame expansion through door 2 (PP13 Run)---(b): Flame expansion through ceiling vent (PP13 Run)

Ignition is followed by the natural expansion of, and flame spread along, the bulk of the accumulated and exiting hot gases. Provided a second vent opening was not opened, the pressure build-up within the compartment would have been such that a backdraught would have been prompted through the single available opened vent.

5.4 WP4 OUTCOME

In regards to the project's last work package, the information dissemination is on its way: this final report including the project's findings and its experimental outcome is being summarised in a journal paper for its near future publication and dissemination. In addition, a further journal paper summarising the results of the work done at the University of Edinburgh – presented as WP1 – is being prepared for future publication.

In terms of the development of operational procedures and/or techniques (in addition to the general guidance outlined under the conclusions of this project), this task is naturally inherited by the adjoining project "Effectiveness of the *gas cooling technique* in larger compartment fires", as it is this new research project is specifically intended to assist in determining the effectiveness of current firefighting procedures and techniques in large compartment fires.

The project's final task is to raise awareness through the publications that all relevant changes found to today's common practice – in building design and fire-fighting tactics – need to be implemented in the Building Regulations; more specifically in Approved Document B.

5.5 PROJECT CONCLUSIONS

The conclusions from this research project are summarised under three sub-topics:

5.5.1 Operational Guidance

Single-sided Natural Venting

PROS:

Venting through a single compartment side opening clearly:

- Improves the visibility conditions in both rooms 1 and 2; and
- Reduces the average gas temperature in the vented room. In this setup, the latter would be room 1 (i.e. the *smoke room*) when the ceiling vent was tested simulating a broken pavement light, or room 2 (i.e. the *fire room*) when the door was tested simulating a door opened by the firefighters.

CONS:

Nevertheless, these improvements come at the expense (i.e. consequences) of:

- Fire growth in the area surrounding the fire (in this case a roaring fire in room 2 which is evidenced by the increased temperatures in this room) and, therefore, higher probabilities of developing a flashover in that room.

- Fire spread along the route to the outlet vent and, therefore, a potential backdraught through any of the opened vents.

In terms of the first apparent consequence, fire-fighters can typically cope with roaring fires so this would not be in principle a serious issue in relation to their safety.

Nonetheless, in regards to the second apparent consequence, fire-fighters cannot deal with backdraughts which pose a real threat to their safety and, in extreme cases, to the stability of the structure on fire.

Potential Remediation with Available and Suitable Openings

Therefore, in situations where fire-fighters find a series of potential indicators or warning signs which may lead to a backdraught – typically in poorly ventilated fires, e.g. basement fires (refer to section 4.2) – the use of an offensive ventilation tactic such as a *natural cross-flow* approach (when potential openings are available and suitable) appears to be a practical solution that minimises the likelihood and severity of any potential backdraught. There is of course a risk that the hot combustible gases may also ignite as they are vented and meet fresh air outside the building, but this is a far less serious consequence that once more fire-fighters can typically cope with, posing a very low risk of human injuries.

Potential Remediation with Unavailable or Unsuitable Openings

In situations where there is no physical way of opening a clear cross-flow path – e.g. in basements with a single opening – *dilution* appears as the only effective solution (refer to section 4.2 for further details on this technique). The method of spraying water mist by the fire-fighters has proved very effective in reducing the average gas temperatures in small compartments, and in reducing the likelihood and severity of a backdraught provided that the dilution is sufficient. If the volume fraction of the unburnt gases is below the critical fuel volume fraction, then the risk of a backdraught is completely eliminated. It is important that as little fresh oxygen as possible is introduced during the water mist spraying by the fire-fighters, and therefore it could be very beneficial to use tools such as piercing nozzles or cutting extinguishers if the building construction materials and layout allow for.

If the volume fraction is still above this critical value, the danger of backdraught lasts much longer. This is evidenced in larger compartments where in theory achieving a sufficient dilution is more difficult. This study is subject of the adjoining project "Effectiveness of the *gas cooling technique* in larger compartment fires" also funded by the FSRTT, as described in 5.2.4.1.3 and mentioned in 5.2.4.2.1.

5.5.2 Education

It was found that the laboratory setup could easily be used by fire brigades for didactic purposes, as a previous phase to real-scale practise exercises, due to its simplicity and robustness to reproduce extreme fire behaviours in a clear, small-scale and controlled fashion.

5.5.3 Information Dissemination

As fire-fighters enter an under-ventilated compartment fire, there is a risk of a sudden fire development that may come in the form of a backdraught. As it has been exposed, while some brigades have specific guidance in place regarding procedures for approaching and fighting such fires, this guidance is, for the most part, based on anecdotal evidence, having been instigated following incidents involving fire-fighter injuries or fatalities.

Nevertheless, before any operational procedure and/or technique could be developed for example ideally after the outcome of the adjoining project "Effectiveness of the *gas cooling technique* in larger compartment fires", it can definitely be concluded – after the summary of the research to date, section 4.4, the experimental results of this research project, section 5.3.7, and the operational guidance outlined, section 5.5.1 – that venting an under-ventilated fire via a single opening (e.g. through a pavement light or via a second compartment) cannot be relied on as a safe practice for fire and rescue services to be used during fire-fighting.

However, there are building regulations – e.g. Approved Document B in the UK – which currently include recommendations for features intended to assist fire-fighters which, as stated above, cannot be used operationally due to uncertainties in their safe method of use.

The project's final task is therefore to raise awareness through publications that all relevant changes found to today's common practice – in building design and fire-fighting tactics – need to be implemented in the Building Regulations. More specifically the topic of venting basements in Approved Document B needs to be updated before new research shows a better approach to fire safety in basement configurations.