BRE CENTRE *for* FIRE SAFETY ENGINEERING
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Capability of the 'cutting-extinguishing' approach in under-ventilated fires

FINAL REPORT

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Date:	**January 2018**

Executive Summary

The final report of the *"Capability of the 'cutting-extinguishing' approach in under-ventilated fires"* project, funded by FSRTT, is presented.

This research project was carried out at the University of Edinburgh from May to December 2017.

The literature review identified research publications which showed that:

- Water mist behaves like a total flooding agent, and is effective in sealed compartments as well as those with openings.
- A very high percentage of water mist droplets are evaporated, resulting in very effective cooling.
- However, it was observed that re-ignition of fires or fire growth may occur once the water mist is switched off, that is, the technique is a suppression system, not an extinguishing system.
- Trials of a cutting-extinguishing system in Sweden have been very positive, and the system has been adopted by many fire brigades. It is seen as a great benefit to fire-fighter health & safety.
- Numerical simulation of the technique has shown that the high momentum nozzle pushes tiny droplets a long distance into a compartment, with increased stirring, resulting in excellent suppression capabilities.

Reduced scale experiments have been carried out in a two-compartment apparatus. Two series of tests have been carried out to investigate the ability of an application of water spray, in advance of opening the door, from preventing backdraught once the door is opened, and to compare the effectiveness of the spray at various different injection locations.

It is shown that:

- The crucial factor in minimising the likelihood of backdraught is not the duration of spray action, but rather is the compartment temperature.
- In order to minimise the risk of backdraught, the average upper layer compartment temperature needs to be reduced to below 180°C using the water spray.
- The effectiveness of the water spray in cooling the compartment temperature is unrelated to the relative locations of the injection point and the fire. That is, fire-fighters do not need to know the fire location to effectively cool the compartment.

The findings of the project will be disseminated directly to fire brigades and through various publications. Discussions will be established regarding operational guidance.

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 and is generally prohibitive in nature, having been instigated following incidents involving fire-fighter injuries or fatalities. Such guidance as is available is not based on investigation into the behaviour of fires in basements or on a scientific understanding of under-ventilated fire dynamics in general.

To address this issue, and increase understanding of under-ventilated fire dynamics and appropriate fire-fighting tactics, two previous research projects have been carried out at the University of Edinburgh, funded by the Fire Service Research & Training Trust (FSRTT).

The first project "*Strategies for Fire-fighting in Basements*" investigated fire behaviour in ceiling vented compartments, and the use of ventilation as a strategy to reduce the likelihood of backdraught or rapid fire growth events. It was demonstrated that a cross-ventilation strategy was best for avoiding backdraught, that is, where the fire compartment was ventilated from both sides, creating a through path for ventilation. Ventilating from only one side, whether from the side or in the ceiling, was shown to be an undesirable strategy.

The second project "*Effectiveness of the Gas Cooling Technique in larger compartment fires*" investigated the strategy of briefly opening the door to a fire compartment and spraying water into the hot upper layer. It was shown that short pulses of spray had a far more beneficial effect than longer water applications, for the same volume of water deployed. The effect of compartment size on the effectiveness of this technique was also investigated and it was found that the technique had limited effect on cooler upper layers, such as might be found in larger compartments. This technique, however, still involves the risk of opening the door to a fire compartment.

The third project, described here, was an investigation, at reduced scale, of the potential effectiveness of systems able to introduce water spray directly into closed fire compartments, without the door being opened. These "cutting-extinguishing" systems cut small penetrations into a fire compartment wall or door and inject water spray directly into the compartment. The aim is to suppress or extinguish a fire before any doors are opened. However, such systems are often used 'blind', with no visual indication of their effectiveness on a fire.

2 PURPOSE

This project provides an experimental and analytical assessment of the '*cutting-extinguishing approach*' where a high-pressure water jet/spray is applied from outside the fire compartment after piercing the external compartment wall.

It is hoped that the results of this project, along with the previously funded studies, will be used to develop simple guidance, in collaboration with fire brigades, which may be used in fire brigade practice, to decide when each technique is appropriate and which technique is the most efficient way to approach and tackle any given under-ventilated compartment fire.

Guidelines will consider (1) reducing or preventing the risk of a backdraught and (2) thermally managing the conditions in an enclosure for search and rescue purposes, and ultimately for extinguishment.

A theoretical analysis has been carried out, and a programme of reduced-scale fire experiments was performed. These experiments establish the effectiveness of this approach compared to the previously studied techniques. The following questions are addressed:

1) What is the minimum volume of water spray which should be applied in order to minimise the possibility of backdraught in the volume considered (Series 1)?

2) To what extent is the effectiveness of the approach dependent on the relative positions of the fire and the water spray injection point (Series 2)?

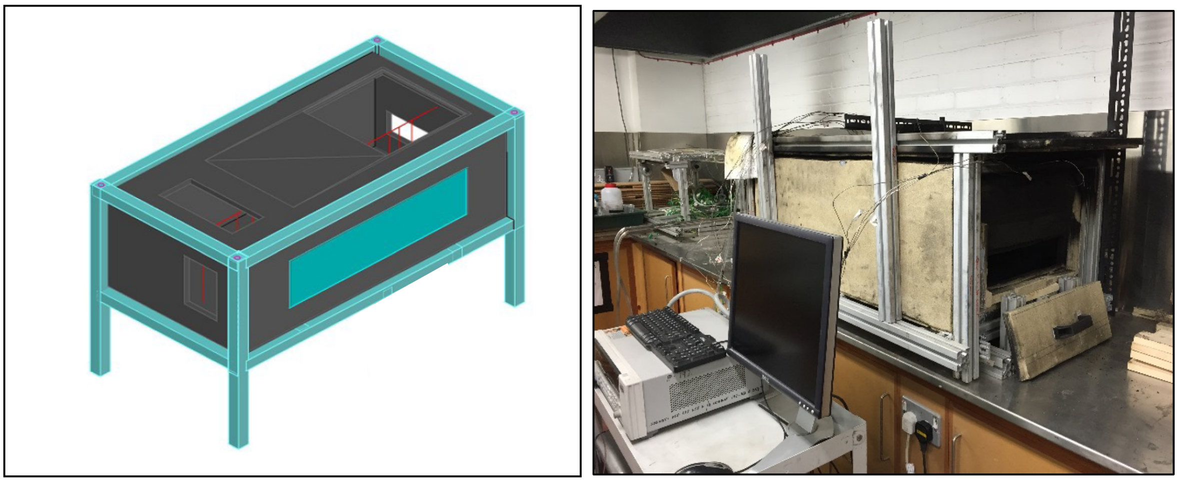

Figure 1: Schematic and photo of the small scale apparatus being used in the current "gas cooling technique" study funded by the FSRTT

The previous study investigated the changing fire dynamics in compartment fires when water spray was applied directly to the upper hot layer, with a focus on developing simple operational guidance, which may be used by the fire brigade, to decide when and how to intervene in under-ventilated fires.

The current project built upon the success of the past studies by considering changes in (1) the combustibility of the hot upper layer after applying water spray and (2) the overall compartment thermal conditions, and also by offering results that will help examine and reconsider the operational guidance already in place in this respect.

The small scale experimental apparatus used in the previous studies, see [5], was also used in the current project. The compartment is fitted with two vertical openings (i.e. doors) and one horizontal opening (i.e. a ceiling vent) which can be opened or closed in various combinations to trigger different modes of fire behaviour and different ventilation patterns. The water spray system developed as part of the previous project was also used in the current research.

The compartment contains an internal sill to allow for a better accumulation of the hot gas layer directly above the fuel bed and therefore enhance the potential for a flashover. This effectively creates a 'two room' situation, which is crucial when considering the relative position of spray inlet to fire, as will be discussed.

3 OUTCOME

This project had two well-defined outcomes:

1. A greater knowledge and understanding of the changing thermodynamics of the hot upper layer in under-ventilated fires when water spray is applied directly into it, or into a volume nearby.

2. Clear results, readily available to be exploited as a validation tool in full-scale tests (e.g. a flashover/backdraught training container) towards developing simple guidance on the optimum way to use the cutting-extinguishing technique for fire-fighting and rescue purposes.

4 PROGRAMME OF WORK

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

WP1. Technical review of available market products, review of current firefighting guidance, and applicable theoretical research.
WP2. Experimental investigation using existing small-scale apparatus to investigate the effect of water spray application on the conditions in the compartment.
WP3. Analysis of the results and onset of discussion on simple guidance on the optimum way to use the cutting-extinguishing technique.
WP4. Disseminate information through publications and directly to the fire brigades and related organisations.

5 PROJECT IMPLEMENTATION

5.1 WP1 - RESEARCH TO DATE – LITERATURE REVIEW

This subsection summarises what mainstream research relevant to the *cutting-extinguishing technique* has found so far, including any recommendations made. Papers relating to water mist without the cutting elements are of relevance and are included here. Rather than exhaustive, this is a summary of the most relevant publications on subject to date:

Assessment of Fire Suppression Capabilities of Water Mist, Julien Gsell, Pg.dip. Msc. Fire Safety Engineering, University of Ulster, 2009/2010 [1]

This report praises the positive impact that the cutting extinguishing technique had in the years preceding its publication, and highlights the need to further explore the abilities of the technique. As such, this report had been prepared with the aim of answering some of the unexplored questions to that date, as well as investigating further on some induced effects after the introduction of water mist in an enclosure. It is based on the analysis of a series of full-scale experiments, carried out in a 60 m^3 compartment.

The most relevant conclusions are the following:

- It was observed the water mist behaved like a gas, in the sense that it can be considered as a total flooding agent. Whether the water mist was injected into a sealed enclosure or into an opened enclosure with a 2.71 m^2 opening, this seemed not to influence drastically the behaviour and pattern of the water spray.

- Even ignoring the water spray characteristics and droplet size, it appeared that droplets were small enough to achieve close to 100% vaporisation. This meant that the majority of the extinguishing ability of the water spray is through a combination of gas cooling, flame blowing and radiation shielding, and minimal results through oxygen depletion and surface cooling.

- In regards to visibility and gas mixing, it was found that the introduction of water mist did not worsen the visibility, neither did it disturb the lower oxygen layer, thus allowing, in theory, the survival of a potential victim during the extinguishing phase. In addition, it was found that the radiative heat flux at floor level was below 2 kW/m^2, only twice as much as that expected on a sunny day in the South of France which could be sustained by a potential victim lying on the floor for an extended period of time.

- It was found that the 3 main parameters influencing the water spray extinguishing capabilities within a compartment fire were: (a) the water spray flow rate, (b) the fuel surface, and (c) the size of the compartment opening. The influence of the latter has shown surprising results compared to previous literature: the greater the opening, the quicker the compartment temperatures diminished. The advantages of a sealed compartment make themselves evident when there is a gas expansion and inerting effects involved. Nevertheless, the opposite occurs with the water spray technique as it actually involves a volume reduction as it cools the upper hot layer. When the upper hot layer cools down and

> therefore shrinks, this produces a pressure drop inside the compartment, which will in turn draw fresh air into the compartment and expel the hot gases through the opening. This rapid gas exchange was identified as the primary reason behind the rapid cooling of the compartment atmosphere.
>
> - Finally, it has been observed that even after 3 minutes of spraying it was not possible to prevent re-ignition of the charring material left. The fire re-growth was not comparable to the initial growth stages (i.e. before the water spray injection), but nevertheless this fact highlights the need for completing the extinguishing by wetting all remaining charring surfaces.

As a last comment, the report emphasises the potential of the cutting extinguishing technique to "revolutionise" firefighting by means of avoiding the unnecessary exposure of firefighters to dangerous compartment fire situations.

Cutting Extinguishing Concept – Practical and Operational Use, MSB Report, Swedish Civil and Contingencies Agency, 2010. [2]

Södra Älvsborg Fire & Rescue Service (SERF) conducted, in collaboration with the SP Technical Research Institute of Sweden, scientific studies on the basis of reported and documented experiences from almost ten years' practical implementation of the Cutting Extinguishing Concept (CEC) or methodology in firefighting operations. SERF was commissioned by the Swedish Rescue Services Agency (SRSA) – since 1 January 2009 the Swedish Civil Contingencies Agency (MSB) – to carry out these studies.

The following is, for the most part, a word-for-word translated summary of the MSB Report. While the original report describes and endorses a brand name product, this has been replaced in the text below with the word "SYSTEM".

> Fighting fires from inside burning buildings is, from a worker's health and safety perspective, an occupation with a very high level of risk exposure. There are therefore requirements for the substitution of conventional methods for fighting fires with new methods, which provide an improved working environment for the responders. In response to these requirements, SRSA initiated a program of research and development in 1996 which resulted in the cutting extinguishing tool SYSTEM and lead to a completely new methodology for fighting fires.
>
> The concept or system, which was developed for this methodology, consists of means for detection and scanning with infrared (IR) technology, information and decision support combined with the SYSTEM cutting and extinguishing technical equipment for precision firefighting as well as PPV (positive pressure ventilation) created by a high-pressure fan to optimise the efficiency of SYSTEM. SYSTEM is ready for use immediately on arrival on site. The concept is integrated into normal fire appliances with 1 + 4 firefighters, but is also part of the lighter quick response unit with 2 firefighters developed by SRSA, the First Response Unit.
>
> In 2008 there were about 120 SYSTEMs in operation in Sweden. Approximately 25 in First Response Units and the others in conventional fire appliances. In all, there are now 450 SYSTEMs in operational use in more than 30 countries around the world. These are 103 installed in different types of vehicles, normal standard

fire appliances, heavy airport vehicles and light vans, as well as in different types of ships.

On the basis of the mobilisation and dispatched response actions reports where SYSTEM was used in Sweden (675 operations during the period 2004 – 2008), the experiences have been compiled and distributed under different types of response actions. The results indicate that the distribution is equivalent to what is normal for fire response actions. The conducted scientific studies of the reported experiences underline the importance of SYSTEM's cutting capacity for quickly getting access to the burning compartment or side rooms and taking response action. The studies indicate that SYSTEM is chosen in order to avoid the risk for ignition of the accumulated fire gases and enable the fire to be attacked directly through the building's construction and achieve a quick influence on the development of the fire.

SYSTEM will mainly exercise influence on the fire by a combination of cooling and inerting, i.e. the mixture of fire gas and air will become over-carbonized and turn into an inert gas as a result of the injection of vaporised water. The oxygen concentration will then decrease in relation to the concentration of flammable gases, which then cannot burn (i.e. the flames are suffocated).

The conclusions concerning the Cutting Extinguishing Concept are summarized in the report as follows:

- SYSTEM efficiently cools the fire gases and stops the fire from developing, as well as inerting the fire gases even when the temperature is low.

- PPV (positive pressure ventilation) is facilitated due to the capability of SYSTEM to control the fire gases before the ventilation is started.

- SYSTEM enables a quicker start of the action against a fire and the fire gases during an intervention.

- SYSTEM provides more methods for extinguishing fires which are considered difficult to handle and for getting access to, for instance, fires in double flooring, roofs and attics.

- The tactical choices increase when these different methodologies/technologies are combined, i.e. IR, SYSTEM, and PPV, as well as common-practise safe indoor compartment firefighting.

- High quality education and training will increase the implementation, improve the efficiency and enhance the credibility of the Cutting Extinguishing Concept advantages.

- Damage to property as well as the negative consequences for the environment caused by conventional firefighting using large quantities of water decrease considerably, and often completely, with SYSTEM.

- SYSTEM improves the working environment for firefighters when fighting fires in buildings from the outside.

> - SYSTEM has increased the firefighters' health and safety when responding to fires inside buildings.

The report presents how SERF works with the CEC and this concept in combination with other methodologies and technologies. Also, research concerning the capacity of water and vaporized water droplets to extinguish fires, as well as an overview and results of the experiments which have been conducted with SYSTEM, are presented in the report. Four different cases of fire interventions conducted by SERF in which the CECs have been implemented are presented extensively.

Finally, proposals are made for future work and further development of SYSTEM. These are:

> - SYSTEM is used actively for fire interventions in different parts of Sweden, but there is a clear need for improved knowledge about how the actions for the extinction of fires should be conducted and what the effects of different types of interventions really are. Improved knowledge would enhance and facilitate the exchange of experience and learning lessons within the fire and rescue services and speed up the introduction of the new methodologies and technologies along Sweden.
>
> - An education and training encompassing the whole CEC has been established in Sweden and forms part of the basic training for full- and part-time firefighters, intervention commanders, and fire and rescue chiefs (EU Projects FIREFIGHT and FIREFIGHT II).
>
> - The report stresses that present training establishments and their equipment for conducting fire extinguishing training are not very well suited for exercising the tactics that are needed for the CEC, for instance in respect to the cooling and inerting of the mixture of fire gas and air, in particular in considerably large volume compartments. Therefore, it proposes that the training facilities are adapted so that IR, SYSTEM and PPV can be used more efficiently for training.
>
> - A final conclusion in the report is that the intervention reports clearly demonstrate a need for an improved and developed methodology for learning from the experiences of the response operations. The report states that the present reporting rarely contains an analysis of the appropriateness, efficiency, etc. of the implemented methodology and, on the other hand, that there is a clear need to evaluate systematically the experiences of new methodologies and technologies to allow for learning from the incidents that occur and create better conditions for experience exchange."

Spray Characterisation of the Cutting Extinguisher, Michael Forsth, Raul Ochoterena, Johan Lindstrom, SP Technical Research Institute of Sweden, 2012 [3]

It is claimed that before this study the size and velocity distributions of the droplets in high pressure sprays has only been theoretically estimated and detailed measurements have been lacking. Thus, this study presents the first experimental measurement of the droplet diameters from the cutting extinguisher. Its summary sates the following:

The laser diagnostic technique GSV (Global Sizing Velocimetry) was used to measure drop size distributions and velocities. Comparative measurements of some non-high-pressure systems - piercing nozzles and conventional nozzles - were also performed in order to understand the difference between the different systems. The measurements conducted using these systems were, however, complicated by the existence of large droplets outside the dynamic range of the measurement system.

Experimental measurements show that the spray from the cutting extinguisher is characterized by small droplets. The following characteristic diameters were measured at 10 m distance from the nozzle using 260 bar injection pressure:

- arithmetic mean diameter d_{10}»70 µm,
- Sauter mean diameter d_{32}»170 µm, and
- volumetric mean diameter d_{30}»110 µm.

The latter value confirms previous theoretical estimations that d_{30}»0.1 mm. The velocity at this distance from the nozzle was approximately 7 ms-1 in the spray core. Droplet diameters were found to decrease significantly when foaming agents are mixed into the water:

- d_{10} drops to 40 µm, and
- d_{32} to 140 µm.

Droplets also seem to be smaller outside the spray core:

- d_{10} drops to 40 µm, and
- d_{32} to 100 µm at an off centre distance of 80 cm from the spray axis.

The volumetric capacity was 57 lmin^{-1}.

These measurements confirm earlier explanations of the efficiency of the cutting extinguisher, and also lead to a more detailed understanding of the extinguishing effect.

1. Cooling, inerting and radiation absorption becomes more effective with these small droplet diameters compared to systems with larger droplets.

2. Furthermore, the fact that small droplets are more prone to follow the air flow than to fall to the floor means that the time available for these suppression mechanisms to act on the fire becomes longer with smaller diameters.

3. The high pressure, resulting in a high speed and high flow, creates a high momentum spray that pushes the water mist long distances into an enclosure fire,

making it possible to act on fires distant from the nozzle exit despite the small droplet size.

4. This could also have the additional benefit in certain circumstances of entraining vitiated air into the fire by the turbulence created.

CFD simulations of the Cutting extinguisher, Robert Svensson, Johan Lindström, Raúl Ochoterena, Michael Försth, SP Technical Research Institute of Sweden, 2014 [4]

This work analyses the cutting extinguisher technique when used for firefighting activities in conventional (idealised) urban structures with the help of computerised simulations. The simulations were done using Fire Dynamics Simulator (FDS) and qualitatively (not quantitatively due to experimental difficulties and model limitations) validated with experimental data obtained from several large-scale fires experiments.

The conclusions of this report are summarised as follows:

- A higher momentum results in an increased stirring of the gases, which results in a more homogenous temperature, leading to a higher temperature close to the droplets and subsequently faster gas cooling and vaporisation of the droplets.

- A higher momentum also leads to a shorter time before the droplets impinge the walls, and thereby become ineffective in these simulations. This effect will be more noticeable as the temperature decreases.

- A higher momentum and increased stirring means that the air exchange through potential ventilations increases, resulting in more water vapour lost to adjacent environments.

- A higher momentum will often contribute to smaller droplets for a real system.

- There are no indications that larger droplets would have a better impact on gas cooling and oxygen reduction.

- The water vapour concentration in the compartment atmosphere substantially increases – with several variables playing together like compartment size, ventilation size, fire size, spray characteristics, etc. – after varying times of injecting water spray by the cutting extinguishing technique, in some cases until the relative amount of oxygen falls to the point where combustion can be hindered or even damped.

- Results from the simulated living room runs showed that up to 80% of the injected water vaporised when the averaged gas temperature in the room was about 200~250°C. In contrast, at average gas temperatures as high as 300°C, less than 20% of the water from a conventional low pressure system (i.e. liquid water) vaporised. This provides an indication of the effectiveness of the cutting extinguishing technique for gas cooling.

5.2 WP2 – LABORATORY TESTS

5.2.1 Aims & Objectives

The general *aim* of the experimental phase of the project was to inert the compartment sufficiently using the cutting-extinguishing technique, such that the risk of a backdraught when any of the compartment's openings is opened is minimised, ideally prevented altogether. The *objective* is to assess the technique's efficiency in thermally managing the conditions in a reduced-scale post-flashover compartment fire using a fixed injection point.

5.2.2 Compartment

The small scale (elongated) experimental apparatus used in the previous study [5] was used in the experimental stage of the present project. This apparatus has inner dimensions of 660 mm (W) x 450 mm (H) x 990 mm (L) and three ventilation openings. The compartment structure was built using an inner steel frame 50 x 25 mm in profile, while the housing was constructed from 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 is fitted with two vertical openings (i.e. doors) and one horizontal openings (i.e. a ceiling vent) which have been 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)

The compartment also contains an internal sill to allow for a better accumulation of the hot gas layer right above the fuel bed and therefore enhance the potential for a flashover.

5.2.3 Water Spray Injection System

A water spray injection system similar to that shown in Figure 2 was used in the experiments. This system can spray water at a constant pressure, from a pencil jet to a fine, hollow cone spray pattern, through a brass, adjustable nozzle.

Figure 2: 5 litres capacity, constant pressure, variable cone pattern, steel sprayer.

The maximum working pressure of this sprayer is 6 bar. A pressure gauge, safety valve and decompression valve are fitted in the top of the container and protected by a plastic shroud, which also acts as a filler funnel.

The pump barrel and plated steel piston rod assembly is of strong brass construction, employing a very simple and efficient 'O' ring principle. The complete pump is unscrewed and removed for ease of filling before each test.

The trigger is a very robust, quick action valve, with brass body and internal action. In order to ensure a constant pressure and therefore a constant output flow, a spray pressure control module was fitted between the trigger valve and the spray lance. Once the sprayer tank is pressurised, this module will hold it at the pre-set constant level – lower than the tank pressure – and shut off if it drops below the target pressure in the tank.

Finally, the adjustable brass spray nozzle was set to a constant cone spray pattern for each and every experiment.

5.2.4 Fuel Description

The fuel used in these experiments was a combination of Polypropylene (PP) pellets with n-heptane. The n-heptane was only used to establish the fire; after it was consumed, the fuel load remained as pure mostly molten PP. The selection was based on ease of handling and setup, considering that this fuel produced requires a robust repeatability for comparison and analysis. The optimum ratio of PP pellets to n-heptane was found in the previous projects [6][5] to be 2:1 by weight.

5.2.5 Data Measurement

The temperatures within the experimental compartment were recorded using three vertical thermocouple trees located at different positions along the compartment (see Figure 3), each with four K-type thermocouples at different heights.

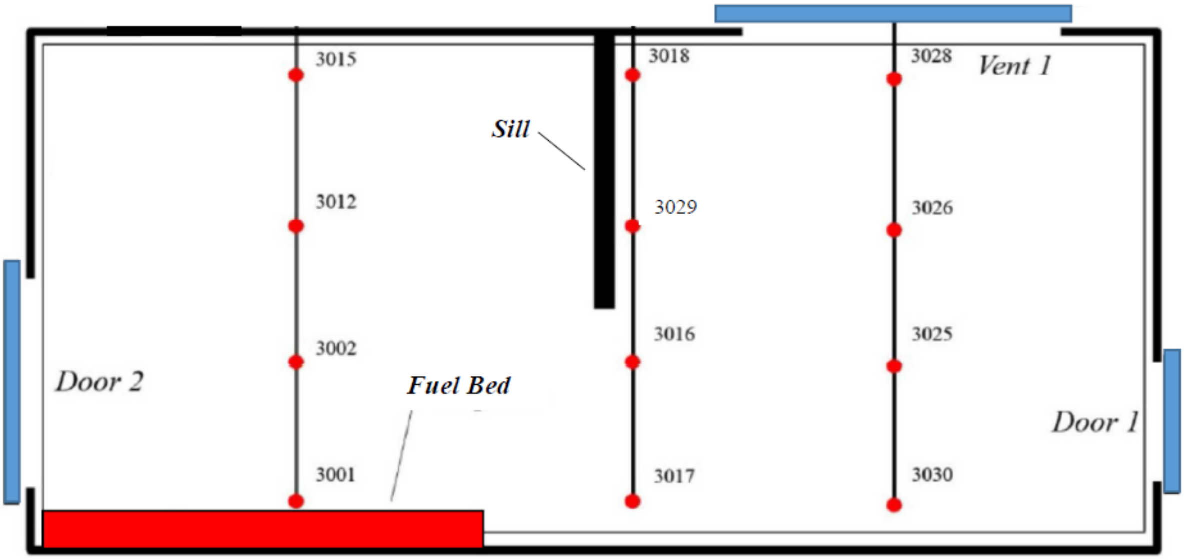

Figure 3: Compartment Side View Showing the Thermocouples Layout. The room to the right is Room 1 (or *Smoke Room*), while the room to the left is Room 2 (or *Fire Room*)

5.2.6 SERIES 1 Tests

During the first series of experiments, in an effort to obtain longer test durations than in the previous two projects but at the same time keep practically the same heat release rate (i.e., nature and fuel bed's equivalent diameter were unchanged), the 20 cm × 20 cm fire bed was loaded with 600 g of PP plus 300 ml of C_7H_{16} maintaining the original 2:1 fuel mixture ratio as explained in 0.

5.2.6.1 Experimental Procedure

The experimental procedure in the Series 1 Tests consisted of the following 3 basic experimental stages:

- Stage 1: Flashover Induction
- Stage 2: Backdraught Test
- Stage 3: Backdraught Avoidance Trial

During the first stage, after the combustible was ignited manually in the fire compartment (i.e., room 2) leaving both door 1 and 2 opened, the signs of flashover in this room were tracked. These were typically smoke combustion within the fire compartment and external flaming through door 2.

During the second stage, i.e. after flashover had occurred in room 2, both doors 1 and 2 were closed in a given sequence and, after a pre-established period of time, door 2 was re-opened in an effort to induce a backdraught through it. If a backdraught occurred, then the conditions prior to sealing the compartment were taken as the minimum conditions necessary – in terms of average room temperatures – to achieve before the different water spray injection trials were tested at the subsequent stage.

During the last stage of this experimental procedure, once the minimum conditions determined at the previous stage 2 were attained, both doors were closed before increasing amounts of water spray – at the same pressure and temperature at each and every trial – were injected in order to reduce the average room temperature. Door 2 was immediately opened after the average compartment temperature had dropped and therefore, the minimum temperature threshold needed to avoid a backdraught, was assessed based on the occurrence or not of a backdraught through this opening.

The results were compared in equal scale time-temperature graphs, presented in the following section (section 5.2.6.2), and analysed in section 5.3.1.

5.2.6.2 Experimental Results

The following graphs are representative of the conditions attained after the injection of increasing amounts of water spray along each test at the same location (i.e., injection point B – please refer to section 5.2.7.1 for details/position of this point):

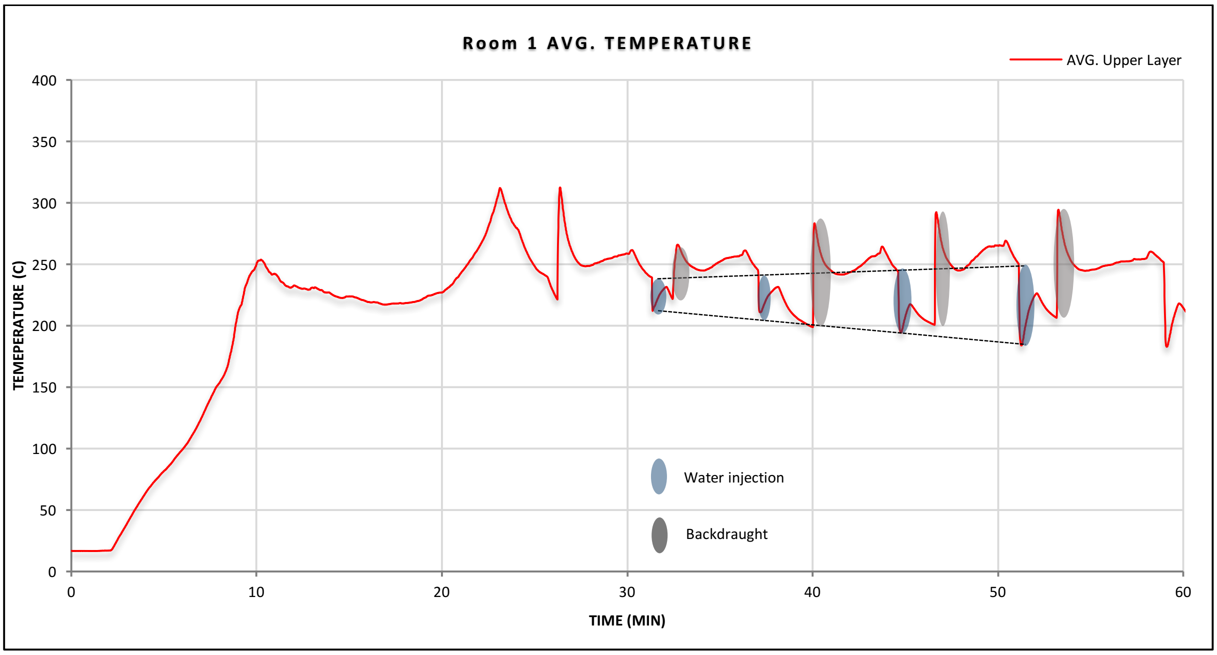

Figure 4: Room 1 (smoke room) average upper layer temperature-time graph (Run 007)

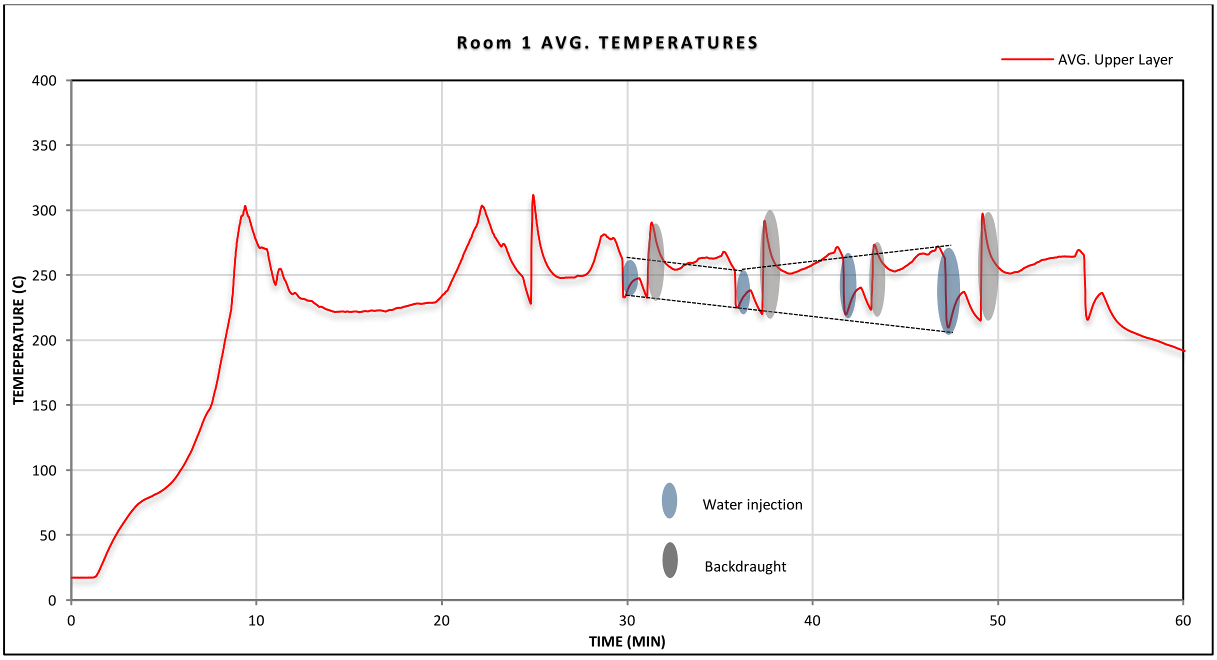

Figure 5: Room 1 (smoke room) average upper layer temperature-time graph (Run 009)

5.2.7 SERIES 2 Tests

5.2.7.1 Experimental Procedure

The experimental procedure in the Series 2 Tests consists of the following 3 basic experimental stages:

- Stage 1: Flashover Induction
- Stage 2: Backdraught Test
- Stage 3: Injection Point Trial

The first 2 stages were exactly the same as in the Series 1 Tests, this is to say:

During the first stage, after the combustible was ignited manually in the fire compartment (i.e., room 2) leaving both door 1 and 2 opened, the signs of flashover in this room were tracked. These were typically smoke combustion within the fire compartment and external flaming through door 2.

During the second stage, i.e. after flashover had occurred in room 2, both doors 1 and 2 were closed in a given sequence, and after a pre-established period of time, door 2 was re-opened in an effort to induce a backdraught through it. If a backdraught occurred, then the conditions prior to sealing the compartment were taken as the minimum conditions necessary – in terms of average room temperatures – to achieve before the different water spray injection trials were tested at the subsequent stage.

Unlike the previous series of tests, during the last stage of this experimental procedure for Series 2, once the minimum conditions determined at stage 2 were attained, equal amounts of water spray (45 ml) – at the same pressure (5 bar) and temperature (lab temperature: ~ 20°C) at each and every trial – were injected at different pre-established locations and the average compartment temperature drop was assessed and compared. Door 2 was immediately opened after the average compartment temperature had dropped, but this time because a backdraught was not the focus of the centre of the analysis, re-ignition was simply triggered by a match.

The injection points chosen were the following:

- A: Directed to Fire – *Close*: this point was located on a wall close to the fire, at mid-height (i.e. at FF height), and no obstacles were present between the fire and the injection point.

- B: Directed to Fire – *Far*: this point was located on the opposite wall far from the fire, at mid-height (i.e. at FF height), and an obstacle affecting the flow dynamics (the sill separating both fire and smoke room) was present between the fire and the injection point.

- C: Not Directed to Fire – *Horizontal*: this point was located on a side wall far from the fire, at mid-height (i.e. at FF height), and because the injection was not directed to the fire, obstacles affecting the flow dynamics were assumed between the fire and the injection point.

- D: Not Directed to Fire – *Vertical*: this point was located on the ceiling far from the fire, and because the injection was not directed to the fire, obstacles affecting the flow dynamics were assumed between the fire and the injection point.

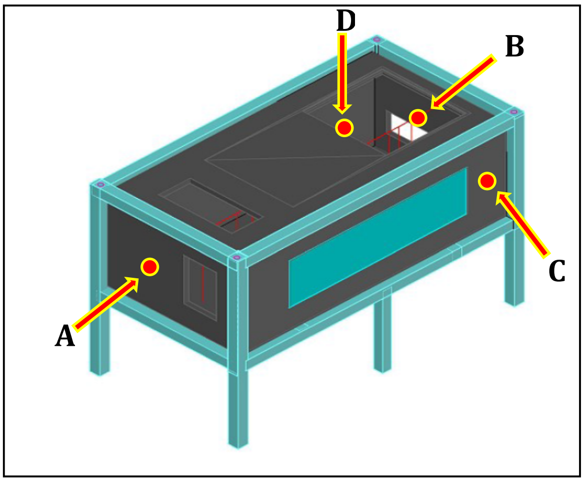

Figure 6: Injection Points

The results were compared in equal scale time-temperature graphs, presented in the following section (section 5.2.7.2), and analysed in section 5.3.2.

5.2.7.2 Experimental Results

The following 4 graphs are representative of the conditions attained after the injection of water spray at all 4 different locations (please refer to section 5.2.7.1 for details/position of these points):

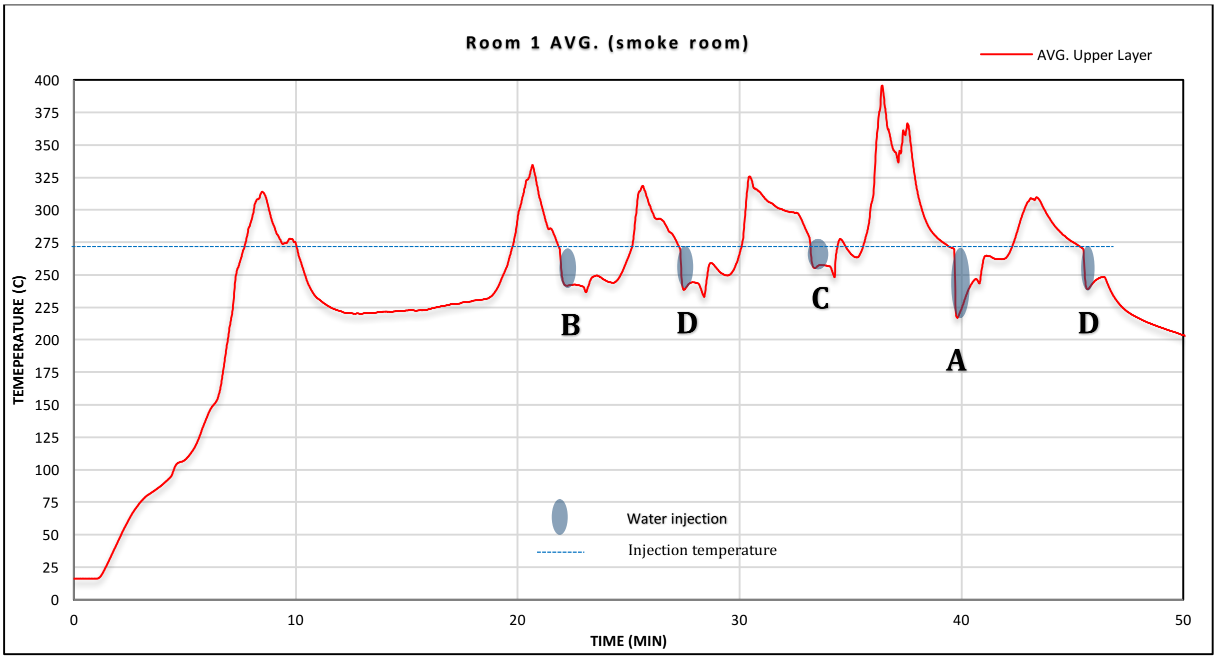

Figure 7: Room 1 (smoke room) average upper layer temperature-time graph (Run 001M)

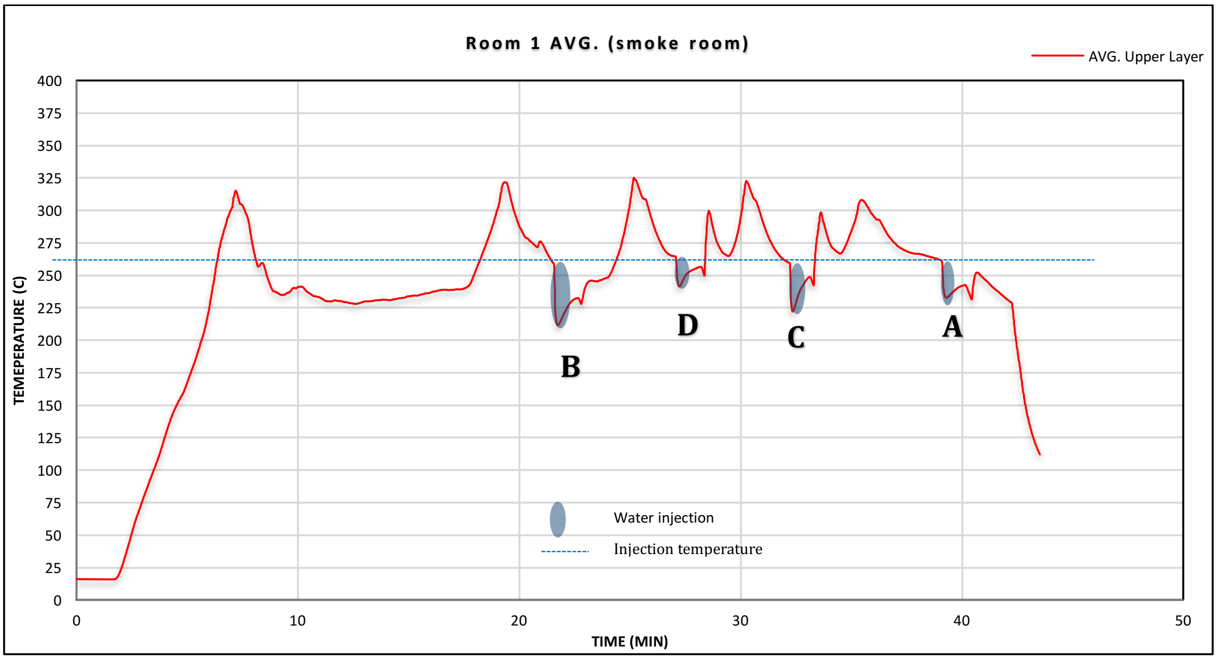

Figure 8: Room 1 (smoke room) average upper layer temperature-time graph (Run 002M)

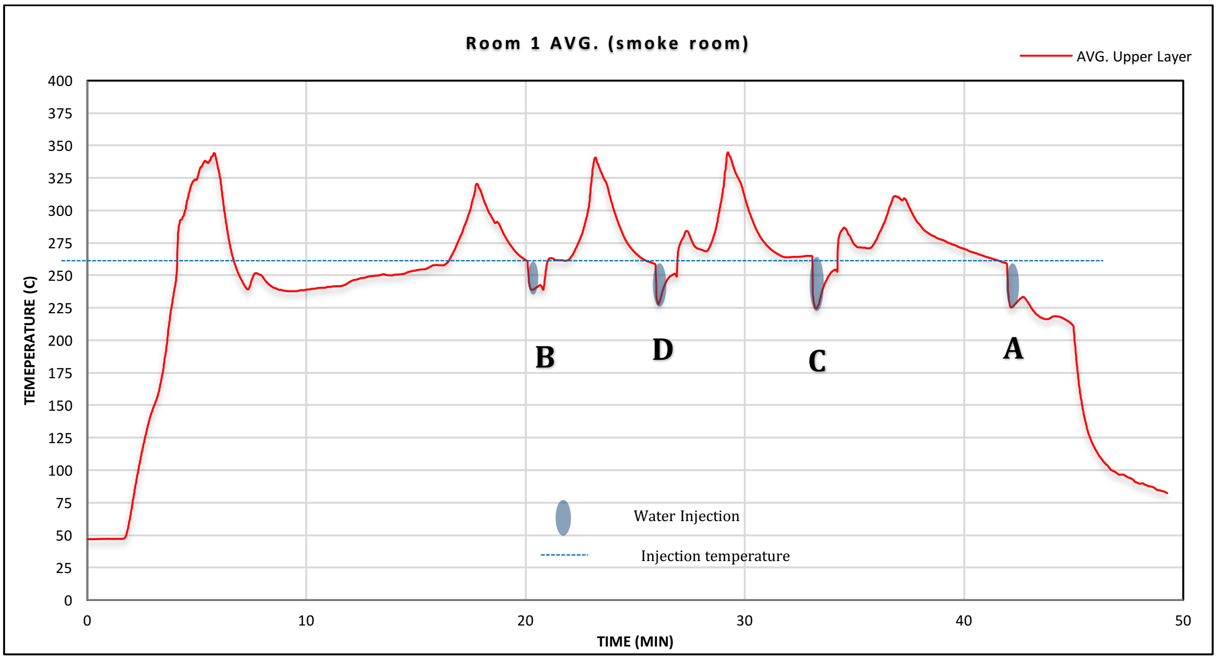

Figure 9: Room 1 (smoke room) average upper layer temperature-time graph (Run 003M)

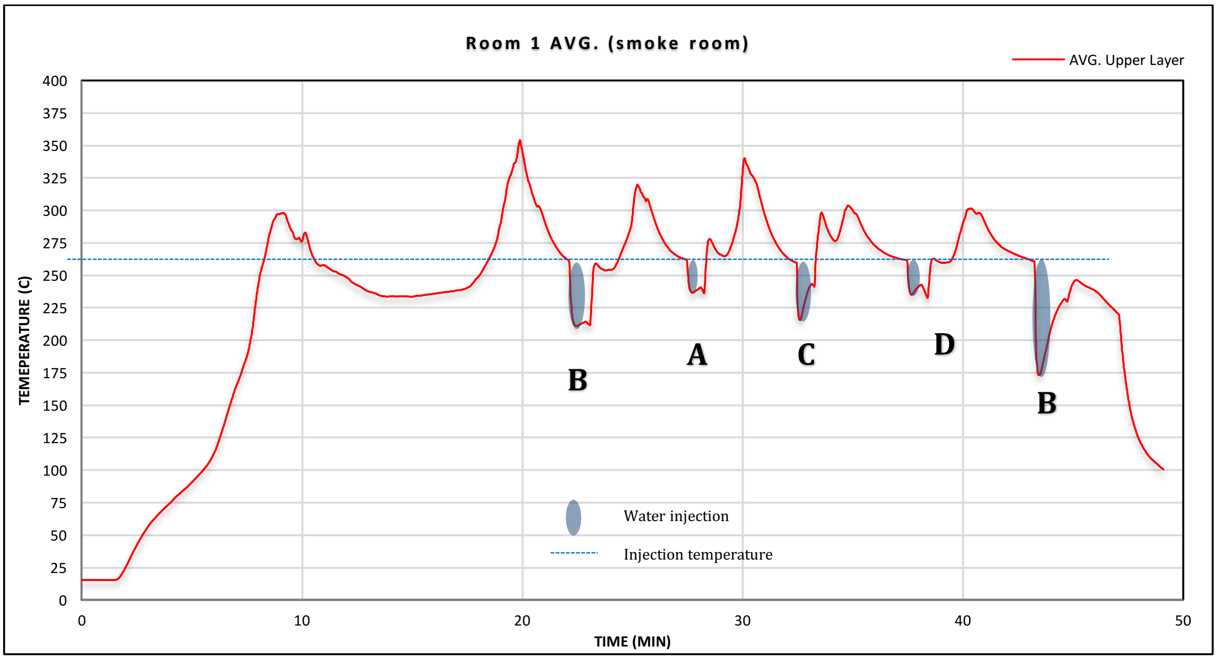

Figure 10: Room 1 (smoke room) average upper layer temperature-time graph (Run 004M)

5.3 WP3 – RESULTS ANALYSIS

Before analysing each series of results, it is relevant to mention that in the same way as in the previous project, the exceptional extinction capacity of the water spray was in part directly related to the PP pellets burning as a liquid or pool fire. Please refer to Section 7.3.1 in the previous project report [5].

5.3.1 SERIES 1 Tests

Figure 4 and Figure 5 show how increasing amounts of water spray injected at equal pressure and temperature produced approximately proportional average gas temperature reductions in the upper hot layer, with backdraughts occurring through the only available opening (i.e. door 2) provided the average upper gas layer temperature did not drop below a certain minimum threshold. In this particular situation this temperature threshold was found to fall around 180°C, and it is related to the volatile combustible mixture auto-ignition temperature.

This finding emphasises the need to find a generalised minimum auto-ignition gas temperature – or safer, a minimum pilot ignition (i.e., ignited by an external source) assuming in real fire scenarios it is likely to have a glowing ember or any ignited debris that would play the role of a pilot – that could be applied to virtually every combustible mixture expected in a typical non-industrial urban fire.

Moreover, these findings after this set of experiments could be translated into water spray application (in litres for example) vs. temperature drop correlations in the same way it was elaborated in Project 2 (Figs. 11 & 12) [5]. Nevertheless, these correlations are a function of the average upper layer temperature which, in practical terms from a fire-fighting perspective, is not really useful as fire-fighters would find themselves in the need to run through theoretical calculations to estimate the amount of water to be injected based on the average room temperature they could work out from thermal camera data.

Minimising the risk of a backdraught is more directly related – and much easier to track in practical fire-fighting terms – to the average upper layer temperature reduction, after the injection of water spray, than to actually how much water is needed to be injected (i.e., the indirect cause). The amount of water will most probably not only depend on the average room temperature, but also on the compartment size, configuration, aspect ratio, etc. and is in realistic terms impossible to extrapolate from these experimental setup and obtain a robust correlation to be used on the field. On the contrary, there is no need to find extrapolation correlations for the average upper layer temperature, and further, it is very easily trackable by the attacking fire-fighting crew with thermal cameras.

In summary, the answer to the question set out in the Purpose Section (section 0) "*What is the minimum volume of water spray which should be applied in order to minimise the possibility of backdraught in the volume considered?*" is naturally: the volume that reduces the average upper layer temperature to below a generalised minimum pilot-ignition volatile mixture temperature. This should fall somewhere below 180°C, according to these results so far.

5.3.2 SERIES 2 Tests

Figure 7 to Figure 10 demonstrate a fairly clear insensitivity to water spray injection location.

This leads to the a-priori conclusion that the water spray injection capacity to cool down an overheated compartment atmosphere is very much independent of the injection point, given the turbulent nature of the flow before - and especially after - injection.

In other words, the good mixing of the technique accounts for any obstacles present – if not directly and very closely blocking the spray injection – in rooms with smaller or similar characteristic dimensions than the length of the water spray cone injected into it, making the spray cooling capacity very efficient from virtually any injection point in small to medium compartment sizes.

The answer, therefore, to the question in the Purpose Section (section 0) "*To what extent is the effectiveness of the approach dependent on the relative positions of the fire and the water spray injection point?*" is: no ideal point was found so far with slight differences, very much dependent on the flow conditions at the moment of injection, between them.

5.4 WP4 – DISSEMINATION

The project's aim and objective have been summarised into a presentation delivered at the RE17 recently in November 2017 in Birmingham. This presentation was focussed on the main findings on the related previous FSRTT funded Project 2 [5], following yet another presentation based on Project 1 [6], also presented at the RE16 conference the previous year in November 2016. A presentation of the current results is intended for RE18 in November this year.

In addition, journal papers summarising the results of all 3 inter-related projects are in preparation for future publication and dissemination. A web page of results is intended and, possibly, a YouTube video presentation of the findings will be produced.

In terms of the improvement of operational procedures related to the g*as cooling and the cutting extinguishing technique*, this task is being shared with the fire brigades (London Fire Brigade and Scottish Fire and Rescue Services) through ongoing discussions and exchange of reports and specific training information.

These discussions will continue long after the conclusion of this project.

6 FINAL DISCUSSION: GENERAL FIRE-FIGHTING STRATEGY FOR UNDER-VENTILATED COMPARTMENT FIRES AFTER PROJECTS I, II & III.

Fires in basements and other restricted access / restricted ventilation spaces 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.

The first project addressing this issue aimed to provide further scientific understanding of under-ventilated fire dynamics in general, and the specific fire dynamics exhibited in basements when changes in ventilation conditions do occur. The project concluded that venting an under-ventilated fire via a single opening (e.g. through a ceiling opening or via a door to a second compartment) cannot be relied on as a safe practice for fire and rescue services to be used during fire-fighting.

Investigation of the limits of applicability of water spray application through different techniques was the goal of the second and third funded projects.

The method of spraying water spray by the fire-fighters by means of the so called *gas cooling technique* (second project) 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 thermal energy within the compartment is sufficient, and that the technique is applied in short pulses more than in long ones.

It is important that as little fresh oxygen as possible is introduced during the water spraying by the fire-fighters, and therefore the third project proved very beneficial to use tools such as a *cutting-extinguisher* if the building construction materials and layout allow for, exhibiting in principle a clear insensitivity to water spray injection point in small compartments.

These results altogether could be used to develop simple guidance, which may be used in fire brigade practice, to decide when and how to intervene in basements and other under-ventilated fires.

Therefore, in situations where fire-fighters find a series of potential indicators or warning signs that indicate the possibility of extreme events like backdraught, the use of a combined tactic – i.e., the *cutting-extinguishing technique*, followed by the *gas cooling technique*, followed by an offensive ventilation tactic (or any other order depending on the prevalent conditions) – appears to be a practical approach that not only minimises the likelihood and severity of any potential backdraught, but also minimises the fire-fighters' heat and toxic gases exposure.

As a classic and hypothetical example exercise, the following could be the combined fire-fighting teams' order of deployment in extreme compartment fire situations:

1. **Cutting/Extinguishing attack team:**

   While this team is deployed as a first attack, they would need no specific injection location other than ease of access to the exterior boundaries of the fire room. The technique would be applied in pulses more than in constant application mode, using the water in a much more efficient way. In this way, there is a potential for developing a small and light backpack water tank, solving in theory the issue of accessibility which is the main drawback of this high-pressure system (i.e. the hose length). Also, the abundant need of water mixed with additives to pierce through the compartment boundary would need to be replaced with a relatively light and strong wireless piercing tool.

   If this attack – launched for instance by 2 fire-fighters at different locations – does not force the conditions below a theoretical "no backdraught average compartment gas temperature" as monitored through an IR camera on the leader fire-fighter' helmet, it will at least improve the situation for the following attack team.

2. **Gas Cooling attack team:**

   This supporting attach team would subsequently launch the "Door Opening Procedure" followed by the "Compartment Entry Procedure" in much safer conditions than if they were the first to onset the attack. There is a possibility that sufficient thermal energy would have been previously absorbed by the cutting/extinguishing technique and, therefore, the reigning conditions would diminish the overall technique efficiency. This nevertheless, would be less important in conditions that have already been improved not only form a fire-fighting (reducing the possibilities of an extreme outcome), but also from a health and safety perspective.

3. **Ventilation tactic attack team**

   The final attack team, would deploy an offensive ventilation tactic such as a natural or forced cross-flow approach, depending on the availability and suitability of vents and fans, to clear up the space from steam and hot gases, and allow the fire-fighters to proceed to the final stages of extinguishing in a relatively clear and not dangerous atmosphere.

7 REFERENCES

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