BRE CENTRE *for* FIRE SAFETY ENGINEERING
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Effectiveness of the *Gas Cooling Technique* in larger compartment fires
Final Report

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Executive Summary

A research project was carried out at the University of Edinburgh, funded by the Fire Services Research & Training Trust, to investigate the effectiveness of the upper layer gas cooling technique in compartment fires.

When entering a fire compartment, following appropriate door entry procedures, fire brigades commonly employ the gas cooling technique to control the compartment conditions so that they may safely approach the fire. The gas cooling technique involves spraying fine water droplets into the hot upper gas layer, to reduce the temperature and flammability of the upper layer. When employed correctly, this approach mitigates the effects of the fire and may have some suppressing influence on the fire location.

A literature survey has shown that there is a paucity of information on this technique in the scientific literature. However, there are several scientific papers on water mist systems which are directly relevant to this procedure. The available literature is summarised and discussed in this report.

An experimental study was carried out at reduced scale to investigate the effects of this technique on compartment fire dynamics.

With regard to the upper layer temperature it was found that:

- The cooling effect is greater with longer bursts of water
- The cooling effect is greater in hotter upper layers
- The cooling effect is greater when the water is introduced in short pulses, compared to a longer burst of the same volume of water
- The gas cooling technique is largely ineffective with upper layer temperatures below 200°C

With regard to the lower layer temperature (i.e. where the fire-fighters might expect to be) it was found that:

- The cooling effect was largely independent of the duration of the burst
- There was no apparent benefit to using pulses instead of long bursts

These results have been communicated directly to fire brigades, and various publications are in preparation for widespread dissemination.

1 BACKGROUND

Typically, the approach to entering a compartment in a fire situation, for both fire-fighting and rescue purposes, consists of (a) *door opening procedure* and (b) *compartment entry procedure*.

During the latter, one of the water application techniques to control the environment within the compartment is to apply pulses of water spray directly into the hot upper layer, with the intention of extinguishing the flames and/or reducing the temperatures in the hot gas layer, and reducing the likelihood of flashover, backdraught and fire gas explosions.

This water application technique – namely the *gas cooling* technique – is nevertheless not always effective. The purpose of this project is therefore to investigate which application methodology and what compartment conditions or characteristics increase or otherwise diminish its efficiency.

2 PURPOSE

This project aims to provide an analytical and experimental assessment of the so-called *gas cooling technique* where water spray is applied directly into the hot upper layer in compartment fires. It is intended that the results of this study would be used to develop simple guidance, in collaboration with fire brigades, which may be used in fire brigade practice, to decide when it would be effective or otherwise ineffective to employ such technique. Guidelines with regard to compartment size and overall volume would be devised, specifically considering the reduction of temperatures in the hot gas layer (as part of the *compartment entry procedure* – refer to section 4.2.2).

A theoretical analysis and literature review was followed by a programme of reduced scale fire experiments. These experiments established:

1) The difference between constant vs. pulsing water application techniques, with regard to the upper layer temperature drop.

2) A correlation between the water spray application and the upper layer temperature drop as a function of compartment size and volume.

The experiments follow directly on from the investigation into fire dynamics in basement fires, funded by the FSRTT in 2015-16. This previous study looked at understanding the changing fire dynamics in basements when changes in ventilation conditions occur. The present project built upon the success of the past study by considering changes in (1) temperature and (2) combustibility of the hot upper layer after applying water spray, and also offers results that will help inform and update the operational guidance already in place in this respect.

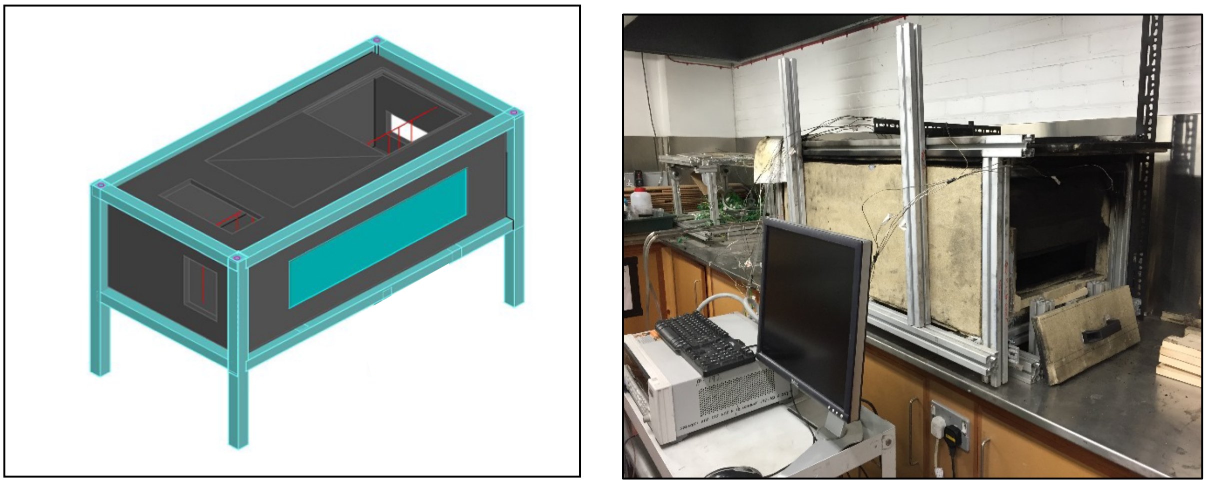

Figure 1: Schematic and photo of the small scale apparatus being used in the current "basement fire" study funded by the FSRTT

3 OUTCOME

This project has two well-defined outcomes:

1. Greater knowledge and understanding of the changing thermodynamics of the hot upper layer in compartment fires when water spray is applied directly to it (*analysis*).

2. Clear results (*correlations*), readily available to be exploited as a validation tool in full-scale tests (e.g. flashover/backdraught training container) towards developing simple guidance on when it is effective or otherwise ineffective to apply the *gas cooling technique* based on the compartment size and overall volume, in respect to reducing the hot gas layer temperature for compartment entry purposes. This will be of direct relevance to the fire brigade.

4 DETAILED TECHNIQUES AND PROCEDURES

Compartment fires are extinguished following certain *procedures* and using various water application *techniques* depending on the circumstances. It is important to note that there are not set instructions that can be followed on every occasion, as every fire incident is and will be different. Any fire-fighter or team of fire-fighters involved in a compartment fire should keep a constant check on the environment surrounding them to ensure that the correct technique is applied.

The following is a summary of the typical procedures and techniques to tackle a fire in a compartment.

4.1 TECHNIQUES

Water application techniques in compartment fires can be grouped under three main headings [1]:

1. Indirect
2. Direct
3. Gas Cooling

Indirect water application is where water is directed from outside the compartment into the flammable gases in the hot upper layer and onto the compartment boundaries. Its purpose is to extinguish the fire by producing large quantities of steam, and avoid any potential backdraught. The branch in this technique is set to medium spray and aimed above and around the fire ensuring maximum coverage. The effects are:

- It cools and dilutes the fire gases.
- It cools the compartment structure.
- It can only be applied from outside the compartment due to the large quantities of steam produced.
- The large quantities of steam produced 'smother' the fire.
- It lowers the neutral plane, reducing vision and worsening conditions for fire-fighters and any casualties in the compartment.

Direct water application is where water is applied directly on the seat of the fire. It can be applied on a fully ventilated fire, a fire in its early stages, or when the fire gases are under control. Its purpose is to extinguish the fire. The branch in this technique is set to a solid or narrow spray that is directed at the base of the fire. The effects are:

- It extinguishes the fire.
- It has the potential for excessive water damage.
- Air can be entrained into the compartment and fire, intensifying the reaction when initially applied.
- When used in a compartment with limited ventilation where a hot upper gas layer (an 'overpressure') has developed, it has the potential to lower the neutral plane and worsen the conditions for fire-fighters and casualties.

One of the key objectives of fire-fighting in the built environment is to control the environment so that the ultimate goal of extinguishing the fire can be effectively performed and safely achieved. ***Gas cooling*** is used to control the environmental conditions within a compartment fire, and reduce the likelihood of flashover, backdraught and smoke explosions. It is an ongoing dynamic process which provides a safe approach route to and from a fire situation. When gas cooling, there are three different techniques used:

i. Short Pulse
ii. Long Pulse
iii. Painting

The purpose of the ***short pulse*** is to provide a safe zone by cooling the gases in the immediate vicinity of the fire-fighting team. It can also be used as a gas temperature check by aiming it into the hot upper layer directly above the fire-fighters and observe the effects: water seen or heard falling back to the ground will indicate that the immediate area above the team is cool enough to advance further into the compartment. The force of the water spray hitting the smoke layer can produce a wave of gases that travels through the room and after the exit. The branch in this technique is set to a medium to wide spray. The width of the spray should be determined by the height of the ceiling: the higher the ceiling, the narrower the spray setting in order to give the water spray the necessary momentum to reach the ceiling level. The effects are:

- Cools the flammable gases.
- Dilutes the flammable gases.

The purpose of the ***long pulse*** is to extinguish the flaming combustion in the upper gas layer, by cooling and diluting, and allow the fire-fighters to advance through the compartment. The branch in this technique is set to medium spray aimed directly into the ignited upper layer gases, ahead of the fire-fighters. The width of the spray and how long the pulse lasts should be adjusted depending on the penetration required to reach the back of the compartment (refer to Section 7.2.6). If the pulse is too quick, the spray will evaporate before it can travel all the way through the compartment. Therefore, the size (and especially the height) of the compartment dictates the water spray cone's size: larger/taller compartments would require narrower spray cones, while smaller/lower compartments would require wider spray cones. The size of the room also dictates how many spray pulses are needed: most compartments can be handled with 3 (side, side, and middle, in an anti-whirl motion); nevertheless, in large compartments 5 could be required, or if the fire-fighting crew is making their way up a corridor, only 1 could suffice. The effects are:

- Cools the flammable gases.
- Dilutes the flammable gases.

Painting is not a pulsing technique. It is an adaptation of the direct water application method but is used with more control and direction, with the purpose of supressing pyrolysis and extinguishing the fire. The branch is opened to allow the least amount of water possible needed to penetrate and supress the fire, and the spray aimed directly onto all the ignited combustibles.

4.2 PROCEDURES

The *door opening* and *compartment entry* procedures can be viewed in further detail as follows:

4.2.1 Door Opening Procedure

- Locate the door, and assess it using the '3 Hs': *Hinges* to identify the direction of opening (towards/away from fire-fighters), *Handle* to identify the opening mechanism, and *Heat layer* to identify potential conditions in the compartment beyond the door (the lower the dangerous the conditions are). The latter is checked ideally using the TIC (thermal imaging camera), or by wetting of the door from top down to ascertain from steaming the level of the neutral plane within the compartment.

- The fire-fighters carry out an assessment of the conditions outside. This involves looking for any signs of extreme fire development, including flashover, and the potential for a backdraught or fire gas explosion.

- A wet test is carried out on the door by discharging an initial *safety pulse* – i.e. a short mist water application towards the door and the ceiling directly above the fire-fighters – the purpose of which is to cool down and dilute (i.e. 'neutralise') any fire gases which have escaped the fire compartment and collected in the ceiling area immediately outside the compartment and above the fire-fighters. Cooling of these gases ensures that if/when the door is opened, no ignition of these gases can occur.

- Positioning of fire-fighters and control of door to ensure the safety of the attacking/rescue crew is maintained during the *door opening/compartment entry* procedure. The door to the fire compartment provides protection for the team making a potential entry, therefore, it should be kept intact – or with minimum damage if forced entry is required – as it offers team's maximum protection.

- The door is then partially opened, enough to allow the fire-fighter branch operator to take a visual reconnoitre inside the compartment, assessing the conditions, observing the rough size and layout of the compartment, and looking for casualties or any other hazards.

- Before closing the door, a pulse of water spray is applied directly towards the ceiling inside the compartment, and the conditions observed to identify the reaction of water application and assess the next action.

- Where conditions are deemed unsafe – i.e. when signs of flashover/backdraught exist – then the *door opening* procedure is repeated as many times as necessary until the conditions are safer.

- If it has been confirmed that no casualties are involved, depending upon the position of the fire inside the compartment, the team should consider extinguishing the fire by *direct* or *indirect* water application (refer to 4.1) from outside the compartment.

- For the *indirect* water application, water spray is directed from outside the compartment into the flammable gases in the hot upper layer and onto the compartment boundaries, and the door is immediately closed to allow the large quantities of steam to cool down and dilute the upper gas layer, avoid any potential backdraught, and ideally suppress the fire.

4.2.2 Compartment Entry Procedure

- If the conditions are such that compartment entry is necessary (for fire-fighting and/or rescue purposes) and possible (when conditions are deemed safe, i.e. since the very beginning or after repeatedly applying the *door opening* procedure), then entry is made.

- Once inside the compartment and as soon as possible, the team should move away from the door and close it behind to restrict the flow of fresh air into the compartment and avoid further fire growth and/or an extreme fire behaviours like a flashover or a backdraught.

- The application of water by the fire-fighters within the compartment remains a flexible and dynamic process that consists of a combination of the *gas cooling technique* described above (refer to 4.1), where water spray is applied as short and long pulses to ensure progress into the compartment can be made, and the fire attacked and ultimately extinguished by direct application (e.g. painting or solid jet) onto the fire seat.

- With the minimum team of two fire-fighters into the compartment, the team leader should be always looking above and in front, while the remaining team member should be looking above and behind. In most situations, the team will need to rely on hearing and touch senses rather than visual.

- The branch operator (team leader) must be skilled in using the appropriate amount of water – as conditions require – to achieve the maximum gas cooling effect and fire extinguishment whilst avoiding over application.

5 RESEARCH TO DATE – LITERATURE REVIEW

The literature review is centred on the effects the direct application of water spray to a hot gas layer has on the following phenomena in a compartment fire situation:

(1) gas phase cooling,
(2) compartmental and localised (in hot gas layer) oxygen depletion,
(3) flammable vapour dilution, and
(4) hot gas layer radiation attenuation (downwards to fire-fighters)

Due to the lack of research specifically in water spray/mist application by the fire-fighters inside a compartment in fire, most of the information examined and collected comes directly or indirectly from publications concerning water mist systems.

In this regard, this subsection summarises what mainstream research in this field has found so far, in relation to the shared effects that any type of water spray application – a water mist system or a hose pulse shot for example – might have in a compartment fire situation.

The following, rather than exhaustive, is a run-through of the most relevant publications on the water mist subject to date:

- ***On the Evaporation Effect of a Sprinkler Water Spray***, W. K. Chow, Fire Technology, November 1989. [2]

  In this research paper, the authors report a crude model – it does not account for the smoke layer cooling – for estimating the evaporation heat loss due to the evaporation of water drops after the interaction between a sprinkler water spray and a fire-induced smoke layer (i.e., water droplets evaporate while travelling through a hot smoke layer).

  Through a set of numerical experiments, varying the droplet velocity, the smoke layer thickness, and the enclosure dimensions, their results showed the following:

  - When the droplets travel through a hot smoke layer, they are heated (or extract heat out of it) by convection until they reach the boiling point. At that point, the droplets evaporate and further extract heat out of the smoke reservoir by evaporation. The authors, therefore, refer to these heat transfer modes between the droplets and the smoke layer as convective heat loss (C) and an evaporation heat loss (E).

  - They predicted that only the small – diameter < 0.5 mm – drops will evaporate, and that the total heat absorbed by the water (i.e. C + E) is inversely proportional to the droplet diameter, and directly proportional to the smoke layer thickness the droplets travel through.

- The authors report that the evaporation heat absorption (E) is smaller than the convective heat absorption (C), with a maximum E/C ratio of 26% within their experimental conditions.

It is important to mention that the model predicts the heat absorption without accounting for the smoke layer cooling effect.

- ***A Closer Look at the Fire Extinguishing Properties of Water Mist***, J. R. Mawhinney, B. Z. Dlugogorski, A. K. Kim, Institute for Research in Construction, National Research Council Canada, Ottawa, 1994. [3]

This paper proposes a classification terminology for water sprays based on drop size distribution that range between Class 1 to Class 3 sprays, from thinner to coarser sprays, respectively.

It also describes the *primary* mechanisms of extinguishment by water mist, namely (1) heat extraction (cooling), (2) Oxygen displacement[i] (or steam inerting), and (3) radiation attenuation (or radiant heat blocking) and invokes theoretical considerations of what could be considered as *secondary* mechanisms of extinguishment, namely (4) vapour/air mixture dilution and (5) kinetic effects at the molecular level.

All 5 mechanisms are summarised in both the SFPE and NFPA Handbooks (see summary of references [4][5]).

- ***Water Mist Fire Suppression Systems***, J. R. Mawhinney and G. G. Back III, Section 46, SFPE Handbook of Fire Protection Engineering, 5th Edition, 2016. [4]

In this section from the SFPE Handbook, the subsection *Fundamentals of Water Mist Systems* expose three topics of said systems which are relevant in a direct or indirect way to the current research. These are:

1. Mechanisms of Fire Extinguishment and Suppression (originally published by Mawhinney et al.[3])
2. Enclosure Effects, Turbulent Mixing, and Cycling
3. Explosion Hazard Mitigation with Water Mist

Each of them is summarised below, with regards to the subject under study:

[i] Displacement leads to an oxygen depleted atmosphere, in the same way as a fire that consumes the oxygen with no fresh air supply. This means that steam *displaces* while fire *consumes*, and both mechanisms lead to depletion; i.e., to an oxygen depleted atmosphere.

1. Mechanisms of Fire Extinguishment and Suppression [3]

    a. Gas Phase Cooling

    Under this sub-section it is stated that the cooling efficacy of water mist is due to the fact that the water is broken up into many fine droplets, which enhances the evaporation rate. The more water that evaporates, the greater the amount of heat that is extracted from the combustion zone, thus reducing the temperature of the flame and hot gases. In turn, the cooling of the flame reduces the radiation (thermal feedback) to the fuel surface.

    It is also implied here that opposite velocity vectors of mist and hot flow result in the maximum degree of turbulent mixing in the collision zone.

    The subsection finally asserts that in real situations the efficiency of the rate of evaporation of the droplets in the compartment is usually unpredictable and certainly uncontrollable over the range of conditions encountered in fire events. This observation is crucial for the current study.

    b. Oxygen Depletion and Flammable Vapour Dilution

    This subsection explains that both mechanisms can occur on either a localised scale or compartmental scale.

    On the localised scale (i.e. within the smoke layer), as the water droplets are converted to the vapour phase, the volume occupied by the water spray droplets increases over three orders of magnitude. This volumetric expansion can then disrupt the entrainment of air (oxygen) into the burning smoke layer extinguishing it temporarily (i.e., oxygen displacement & further depletion). Also, the injection of water spray into the burning gas mixture (air + vaporised fuel) can push the fuel concentration below the LFL (Lower Flammability Limit) ceasing the burning locally (i.e. flammable vapour-air mixture dilution).

    On a compartmental scale, the production of steam resulting from the water spray interaction with the flames (fire base), hot burning upper layer gas mixture, and/or hot surfaces, can significantly reduce the oxygen concentration (by displacement) in the enclosure. If the concentration falls below the LOC (Limiting Oxygen Concentration), the fire will be extinguished (i.e., oxygen depletion).

c. Wetting and Cooling of the Fuel Surface

This subsection explains that the wetting/cooling of the fuel surface reduces the gasification rate of the fuel. If the combustible vapour-air mixture (above the fuel and/or that comprising the hot gas layer) is reduced below the LFL of the mixture, the flame will be extinguished.

d. Radiation Attenuation and Kinetic Effects

This subsection stresses that water mist and water vapour measurably reduce the radiant heat flux to objects around the hot emitting bodies.

It is explained that radiation attenuation – in a generalised scenario – is the result of the gas phase cooling and the increase in water vapour concentration between the fuel and the flame. Lowering the flame temperature reduces the radiation feedback to the fuel surface. Also, water vapour in the air above the fuel surface acts as a grey body radiator that absorbs radiant energy (from the hot upper layer, walls, etc.) and reradiates it to the fuel surface at a reduced intensity.

This subsection also stresses that kinetic effects may contribute either to flame intensification or to extinction. Possibly the turbulence and entrainment associated with the rapid evaporation at the flame surface (within the upper burning gas mixture for this case) accelerate the burning rate. Contrary, kinetic effects may also be involved in flame suppression, the result of both gas phase cooling and oxygen depletion/dilution. When a diluent (in this case water vapour and recycled, vitiated combustion gases) is added to the combustion reaction, combined with flame cooling, it is hypothesized that reaction rates at the molecular level are significantly different from stoichiometric conditions.

2. Enclosure Effects, Turbulent Mixing, and Cycling

Here, the importance of enclosure effects is emphasised, affirming that they maximize the benefits of gas cooling, oxygen depletion and dilution (refer to 1.a & 1.b.).

Regarding the gas cooling mechanism, a relevant pronouncement in the handbook is that for fires in enclosures, it has been observed that larger fires increase the efficiency of evaporation – as opposed to smaller fires in the same volume – due to heat confinement in the enclosure.

In terms of the oxygen depletion mechanism – and in a compartmental scale – it is stated that the vitiated gases plus water vapour are forced down[ii] by the spray to the seat of the fire and contribute to extinguishment through oxygen depletion.

It is also explained that the hot, vitiated gases collecting in the upper layer of an enclosure are cooled rapidly by the first contact with the water mist. Depending on the temperature and depth of the hot layer, the rapid cooling results in an instantaneous volume reduction, creating a negative pressure that can suck in the windows or walls of a tight enclosure. If the enclosure had reached flashover temperatures before water spray injection, it is remarked that is hard to say which phenomenon would dominate, the expansion due to steam generation or contraction due to cooling. Nevertheless, the author's experience has shown that the rapid cooling of a deep hot layer (by water mist) in a closed compartment can create a sudden negative pressure pulse strong enough to pull in the walls of the enclosure. The experience is contrary to the often cited but unfounded fear of "steam explosion," that is, a strong positive pressure forcing hot gases out of the compartment.

The benefits of pulsing, that is, the on-off action of water sprays, also described as cycling, are described here too. Pulsing the injection of water mist into an enclosure results in more rapid extinguishment, with less total water usage, than continuous application of mist. The compartment temperature rises as the fire regrows during the first off-stage, allowing for more evaporation of lingering fine mist (gas cooling). The resurgent fire further reduces the oxygen concentration in the enclosure (by consumption). The next injection of spray further cools and mixes the oxygen depleted gases. In this manner, cycling appears to lead to greater net evaporation and oxygen reduction than with steady injection. The improvement of the efficacy of water mist in fire suppression using cycling discharges is attributed to the faster depletion rate of oxygen in the compartment and the recurrent turbulent mixing created by cycling discharge. However, it is stressed that the apparent benefit of cycling is likely to be very dependent on the volume of the compartment.

3. Explosion Hazard Mitigation with Water Mist

The SFPE handbook cites a number of studies that have been done to assess the potential for water mist to mitigate explosion hazards. The background plausible hypothesis listed are:

[ii] This applies with a vertical downwards water mist injection. This is not the case in the 'gas cooling technique' where the jet is directed upwards in different angles depending on the situation. In any case, the effect of O_2 depletion and/or high concentrations of CO, CO_2, and water vapour in the lower levels is ONLY desired with extinguishment as an objective, and NOT desired while applying the 'gas cooling technique'.

a. that a deflagration flame front in a pre-mixed combustible vapour, moving through a cloud of finely atomized water droplets would be quenched as it encountered sufficiently small water droplets;

b. that the energy of a detonation shock wave moving through a field of water droplets would be "stripped" by the break-up of spherical water drops; and,

c. that the ignition energy required to ignite a vapour/air mixture would be increased by the presence of the water mist.

It is nevertheless emphasised that a review of experimental work performed over the last three decades reveals that there is mixed opinion about "whether application of water spray will quell or invigorate an explosion", whereas analytical work supports the idea that benefits of using water mist to mitigate explosions are substantial, provided attention is paid to the details of application.

- ***Water Mist Fire Suppression Systems***, J. R. Mawhinney and G. G. Back III, Section 10, Chapter 17, NFPA Fire Protection Handbook, 19th Edition, 2003. [5]

In a similar fashion to the SFPE handbook, this chapter of the NFPA handbook describes and discusses the mechanisms that play a role in extinguishment originally published by Mawhinney et al. [3] – this time differentiated into primary and secondary – together with the enclosure effects. The primary mechanisms listed are:

(1) heat extraction,
(2) oxygen displacement, and
(3) blocking of radiant heat.

The two secondary mechanisms – difficult to quantify their importance – listed are:

(4) vapour/air dilution, and
(5) kinetic effects.

The following summary is an extraction from this chapter mainly in what is relevant to the subject under study:

Heat Extraction (Cooling). When water is applied to a fire, heat is absorbed in three areas: (1) from the hot gases and flames, (2) from the fuel, and (3) from the objects and surfaces in the vicinity of the fire.

Compared with coarser sprays, finely divided water sprays enhance the speed at which the spray extracts heat from the hot gases and flame. Reducing the drop size increases the surface area of the water mass and thereby increases the rate of heat transfer. The conversion of water droplets to steam absorbs heat.

If sufficient heat is withdrawn, the gas-phase temperature of the flame can be dropped below that necessary to sustain the combustion reaction, and flame will be extinguished. Theoretical considerations suggest that the combustion reaction in a diffusion flame will cease if the flame temperature drops below approximately 1,600K (1,327°C).

Oxygen Displacement (definition summary combined with that from reference [6]).
Oxygen displacement can occur on either a *compartmental* or *localized* scale. On a *compartmental* scale, the oxygen concentration in the compartment can be substantially reduced by the rapid evaporation and expansion of fine water droplets to steam, when water mist is injected into a hot compartment and absorbs heat from the fire, hot gases and surfaces. Calculation results showed that oxygen concentration in a room with a volume of 100 m^3 could decrease approximately to 10%, when 5.5 litres of water is completely converted into steam.

The reduction of the oxygen concentration in a compartment by water mist is a function of the fire size, the length of pre-burn period, the volume of the compartment and the ventilation conditions in the compartment. As the fire size or the length of the pre-burn period of the fire increases, both the oxygen depletion due to the fire and the oxygen displacement due to the formation of more water vapour caused by high compartment temperatures are increased. This combined effect significantly reduces the oxygen concentration in the compartment and enhances the effectiveness of water mist for fire suppression.

Injection of a finely divided water spray into a hot compartment (or smoke layer) results in rapid evaporation, expansion, and in displacement of the air in the compartment (or smoke layer) by steam. If the amount of oxygen available for combustion is reduced below a critical level, the fire burns inefficiently and will be easier to extinguish by cooling.

On a *localized* scale, when the water sprays penetrate into the fire plume and are converted to vapour, the vaporizing water expands to about 1,700 times its liquid volume. The volumetric expansion of the vaporizing water disrupts (LOC) the entrainment of air (oxygen) into the flame (i.e. displaces the air in the vicinity of the evaporating drop) and dilutes (LFL) the fuel vapour available for combustion of the fuel. As a result, when the fuel vapour is diluted below the lower flammability limit (LFL) of the fuel-air mixture, or when the concentration of oxygen necessary to sustain combustion is reduced below a critical level (LOC), the fire will be extinguished.

Therefore, in flame suppression (e.g. in the burning smoke layer), oxygen displacement appears to play a stronger role than flame cooling.

The average temperature of the gases in the compartment limits the dilution of oxygen by water vapour in a suppression scenario. This is shown in the following graph:

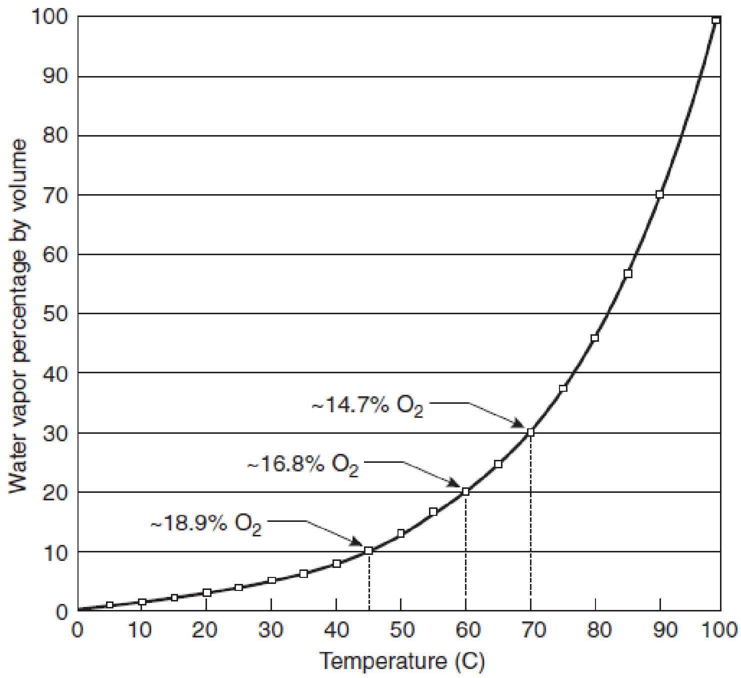

Figure 2: Relationship Between Gas Temperature and Volume Concentration of Water Vapour in Saturated Air (The approximate resulting oxygen concentration is indicated.)

This fact helps explain 2 things:

- *Why water mist is more effective at extinguishing "large" fires than "small" fires in a given compartment?*
  - A "large" fire releases more heat into a compartment in the early stages than a "small" fire, so that more heat is available to evaporate the fine water droplets. This is to say, higher gas temperatures can tolerate higher water vapour concentrations and therefore increase the oxygen dilution by water vapour. Also, "large" fires reduce the ambient oxygen concentration (oxygen depletion by consumption) to the point that combustion efficiency will already be reduced, prior to introducing the water mist. So, with the combined effects of vitiated combustion air (depletion - LOC), plus further dilution (LFL) by water vapour, "large" fires can be extinguished with lower flux densities than "small" fires.

- *Why cycling sprays on and off, in closed compartments, reduces extinguishing times?*
  - More water is evaporated because of the higher compartment temperature during the "off" stage of the cycle.

Moreover, the impact of oxygen dilution by water mist on fire suppression is strongly dependent on the properties of the fuel. This is because the minimum amount of free oxygen required to support combustion varies with the type of fuel. For most hydrocarbon fuels, the critical oxygen concentration for maintaining combustion is approximately 13%. For solid fuels, the critical oxygen concentration required for combustion is even lower: charring solid fuels may burn with oxygen concentrations as low as 7 %. This explains why it is easier to extinguish hydrocarbon pool fires (diesel and heptane) than wood crib fires for example. Relating this fact to Figure 2, it can be deducted that water mist is likely to act as a gaseous extinguishing agent (i.e. extinguishes by oxygen depletion – steam inerting) when the average compartment temperatures are above 70°C for hydrocarbon pool fires.

Radiant Heat Blocking (definition summary combined with that from reference [6]). On a micro (or localised) scale, this mechanism plays a role in stopping the fire from spreading to unignited fuel surfaces and reduces the vaporization or pyrolysis rate at the fuel surface which, in turn, reduces the rate of generation of volatile vapours[iii]. On a macro (or compartmental) scale, water vapour in the air acts as a grey body radiator that absorbs radiant energy, and re-radiates it at a reduced intensity. Radiation attenuation provided by water mist protects objects and personnel in a space from radiant heat damage, whether or not extinguishment occurs.

The attenuation of radiation depends on drop diameter and mass density of the droplets. A given volume of water will provide a more efficient barrier against radiation if it is made up of very small droplets in a dense spray, than a dilute spray with larger droplets. As the concentration of drops with diameters smaller than 50 microns increases, the degree of attenuation of radiant heat increases.

The wavelength of the radiation, however, is also important in determining the radiation attenuation of water mist. The spray will absorb more radiation if the droplet diameters are close to the wavelength of the radiation.

Vapour/Air Mixture Dilution. Air and water vapour entrained in a water spray may dilute the vapour/air mixture to below the lower flammability limit (LFL).

With *diesel* fuels (flash point ~ 60°C), cooling of the flame reduces the thermal energy to the fuel surface, which in turn reduces the rate of evaporation (see Footnote iii). Coupled with a dilution of the vapours by the addition of entrained air and water vapour, the vapour–air concentration falls below the lower flammability limit (LFL).

[iii] thermal feedback – has relevance only in liquid fuels as per Harmathy's theory [12]

In contrast, it is much harder to reduce a *heptane–air mixture* to below its lean flammability limit (LFL) by thermal feedback reduction (i.e. flame/gas cooling and dilution), because of the low flash point temperature (flash point ~ –4°C) and high vapour pressure of heptane.

Dilution of pyrolysed vapours emitted from *solid fuels* may also contribute to extinction. This is referred to as a secondary mechanism, because it is difficult to see how dilution alone could result in extinguishment. It requires uniform mixing of mist and entrained air throughout the space between the flame and the fuel surface to dilute all of the vapour/air mixture within the vaporization region. Mixing at fuel surfaces is often turbulent and non-uniform, so it is likely that there will always be some region of the vapour/air cloud that is in the flammable range.

Kinetic Effects of Mist on Flames. A liquid pool fire is sometimes intensified by the application of water spray. A "flare-up" often occurs during the first moments of contact with the water mist, and it is evident in some fire tests that the burning rate is increased for longer periods. The general flare-up at the instant of application of water spray on liquid fuel fires is familiar to fire fighters. In many cases, the flare-up is followed by a quick knockdown and extinguishment of the flames. If the spray dynamics are insufficient to bring about extinguishment, the fire will continue to burn violently in spite of the mist.

Experimental work quoted here, report intensification of the rate of combustion in the use of water mists to quench gaseous explosions. The authors report that it is "never immediately obvious whether application of a water spray will quell or invigorate an explosion."

It is emphasised that the conflicting influences of cooling, inerting (i.e. oxygen depletion), dilution, and enhanced turbulence and fuel mixing lead to a degree of unpredictability in the effects of water mist on gas-phase burning of pool fires.

Consequently, the subsection concluded that there is reason to be concerned that a water mist system that is unable to extinguish a liquid fuel pool or spray fire could instead increase the heat release rate of the fire and, therefore, that further research is needed to investigate the conditions under which flare-up or flame invigoration occurs.

Enclosure Effects (definition summary combined with that from reference [6]). Enclosure effects enhance the performance of water mist systems. The enhanced performance can be attributed to:

- Restricted ventilation: a fire that is large enough to quickly reduce the average oxygen concentration in a compartment could be considered to be "poorly ventilated" (i.e. oxygen depletion by consumption). The addition of a small amount of water mist and resulting increase in water vapour further reduce the oxygen available to support combustion (i.e. by oxygen displacement + vapour–air mixture dilution). Thus, an under-ventilated fire in an enclosure is "easier" to extinguish than a well-ventilated unenclosed fire.

- Heat entrapment: heat from the fire trapped in the compartment evaporates the finest portion of the mist (increased evaporation/cooling efficiency), so that the expanding water vapour displaces oxygen and fuel vapour around the fire (in a localised scale) and pushes them out of the compartment (in a compartmental scale) (oxygen displacement/steam inerting). Then, oxygen-depleted, hot fire gases at the ceiling of the compartment are cooled by the mist and pushed down to floor level (increased evaporation/cooling efficiency), mixing water vapour (vapour/air mixture dilution), oxygen-depleted air, and water drops with the fire.

The combined effects of reduced combustion efficiency (by oxygen depletion, oxygen displacement, oxygen dilution) and flame cooling (increased evaporation/cooling efficiency) usually result in extinguishment.

The degree of enclosure effects in fire suppression is mainly dependent on the fire size in relation to the compartment size. "Large" and "small" fires are defined loosely in terms of whether the fire will affect the average temperature and oxygen concentrations in the compartment within the activation time of the water mist system.

A "large" fire reduces the ambient oxygen concentration to the point that the combustion efficiency of the fire is reduced, prior to introducing water mist. A "large" fire also releases more heat in the compartment to evaporate the fine water droplets (higher compartment temperatures support higher absolute concentration of water vapour), and further reduces the oxygen concentration in the compartment. With the enclosure effect, the main extinguishing mechanism of water mist for "large" fires is oxygen displacement.

With "small" fires in the compartment, however, less heat and combustion products are released. The reduction in oxygen concentration and the increase in gas temperature in the compartment are small prior to the activation of the water mist system. The enclosure effect no longer has an important effect on the extinguishing performance of water mist, because less heat, water vapour and vitiated gases are available for confinement. The extinguishment of a "small" fire by water mist will depend almost entirely on direct fire plume or fuel cooling.

Where enclosure effects can be relied upon, the flux density required for extinguishment can be as much as 10 times lower than that required for unconfined and well-ventilated fires. In the latter, because there are no enclosure effects to create conditions favourable to extinguishment, water mist must be discharged directly on the fire, and can achieve extinguishment only if the spray has strong enough momentum to push water droplets and water vapour into the flame and fuel surface.

- ***NFPA 750, Standard on Water Mist Fire Protection Systems***, 2006 Edition, National Fire Protection Association, Quincy, MA, 2006. [7]

  In Annex A (A.3.3.17), this standard addresses the use of fine water sprays for the efficient control, suppression, or extinguishment of fires using limited volumes of water. It states that properly designed water mist systems can be effective on both liquid fuel (Class B) and solid fuel (Class A) fires, asserting that factors such as drop size distribution, fuel properties, enclosure effects (function of ventilation and heat confinement), spray density (spray mass/volume), and spray velocity are all involved in determining the effectiveness of the system.

  In regards to the *momentum* of an element of spray (M_w), the standard defines it as the product of its velocity (V_w) and the mass of dispersed water droplets (m_w). It stresses that the term *velocity* implies direction as well as speed, and that it is the *momentum* of a mist in a particular direction, relative to the direction of flow of the hot fire gases, that enhances cooling and suppression effectiveness. This means that opposing directional flows bring about turbulent mixing, and hence improved cooling.

  In sum, all three system variables – *drop size distribution* (DSD), *spray flux density* (F_w), and *spray velocity* (V_w) (speed and direction relative to smoke's) – are involved in determining the ability to extinguish a fire in a given scenario (this of course involves the fuel properties and enclosure effects).

  In Annex B (B.1), this standard addresses that a key mechanism in the successful use of water mist fire protection systems is the increased surface area per unit water volume afforded with the generation and application of small droplets. It further explains that the increased surface area dramatically increases the rate of heat transfer from the fire to the water mist droplet, cooling the combustion reaction and diluting the oxygen concentration with the generation of water vapour in the vicinity of the fire.

  The standard also stresses the importance in water mist systems to characterize the droplet size distribution (DSD), and the importance of measuring the maximum diameter at which a specified fraction of the total volume is accumulated. For example, $Dv_{0.10}$ represents the diameter at which 10 percent of the total volume of the water mist is contained in droplets at or less than the specified diameter. By this definition, $Dv_{0.50}$ represents the volumetric median diameter; that is, 50 percent of the total volume of the total water mist is contained in droplets equal to or less than this diameter, and 50 percent is contained in droplets of greater diameter (also defined in A.3.3.4 as Dv_f).

The definition of water mist in this standard includes sprays with $Dv_{0.99}$ of up to 1,000 μ, including some water sprays used in NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*, some sprays produced by standard sprinklers operating at high pressure, as well as light mists suitable for greenhouse misting and HVAC humidification systems.

- ***The Capabilities and Limitations of Total Flooding, Water Mist Fire Suppression Systems in Machinery Space Applications***, G. G. Back III, C. L. Beyler, R. Hansen, Fire Technology, Volume 36, No. 1, 2000, pp. 8-23. [8]

  This report describes the capabilities and limitations of total flooding water mist fire suppression systems in machinery space applications, after the results obtained from tests conducted in compartments ranging from 100 to 1,000 m^3 and varying degrees of ventilation.

  The interpretation of the test results is based on the fundamentals of the mechanisms of extinguishment associated with water mist. These are well described in reference [5] from the same author.

  The general results summary – i.e. the trends observed during the tests – is taken literally from the report as:

  1) Water mist systems can extinguish fires in minutes, as opposed to fractions of minutes for the gaseous halon alternatives. These times can potentially be reduced by designing the system around the space being protected and by securing the ventilation-forced and natural-to the space before system activation.
  2) Immediately after activation, all of the water mist systems dramatically reduced the temperatures in the space. In most of the tests, the space became well mixed with a uniform temperature between 50 and 70°C. This temperature reduction will help manual intervention, minimize thermal damage, and prevent fire spread from the compartment of origin.
  3) Larger fires were easier and faster to extinguish than smaller fires. This was related to the consumption of oxygen by the fire, the generation of steam, and the turbulence created by the fire.
  4) Lower flashpoint fuels, such as heptane with a flashpoint of -4°C were more difficult to extinguish than higher flash point fuels, such as diesel with a flashpoint of 60°C. This was attributed to the re-flash or re-ignition potential of the lower flashpoint fuels.
  5) Obstructed fires were more difficult to extinguish than unobstructed fires, which was attributed to the amount of mist actually reaching the fire. Obstructions usually result in areas of lower mist concentration and for this reason, require additional oxygen depletion to aid extinguishment.

6) In many cases, water mist systems could not extinguish the small, obstructed fires. Small fires in the presence of larger fires were much easier to extinguish than small fires alone.
7) The systems that produced small drops with high momentum demonstrated superior extinguishing capabilities against obstructed and unobstructed Class B fires. These systems were typically the single fluid high pressure systems.
8) Larger vent openings dramatically reduce the fire-fighting capabilities of the candidate water mist systems. This was related to high mist losses out the vent, a lack of oxygen depletion, and a decrease in steam production.
9) For some systems, increases in the mist discharge rate increased the fire extinguishment capabilities of the water mist system. These performance increases, or reduced extinguishment times, were observed primarily against unobstructed fires.
10) Increases in mist discharge rate had little, if any, effect on the system's fire extinguishment capabilities against obstructed fires. Better mist dispersion through the strategic positioning of nozzles does, however, have the potential to increase the system's performance.
11) Pan fires were more difficult to extinguish than spray fires with the same ambient heat release rate. This was attributed to a reduction in heat release rates of pan fires as the oxygen concentration in the space was reduced.
12) There appears to be a relation between the time required to extinguish an obstructed fire and the size of the fire. This relation is a function of the time required to reduce the oxygen concentration in the space below a critical value. For a given fire scenario, this critical oxygen concentration appears to be dependent on the spray characteristics of the water mist system.

The report concludes that the *strengths* of water mist are associated with its ability to extinguish a wide range of larger Class B fires while thermally managing the conditions in the space. It states that the reduced temperatures minimize the thermal damage and prevent fire spread to adjacent compartments, and that the lower temperatures also tend to reduce the airflow through vent openings in the space making these systems somewhat less affected by the ventilation conditions in the space than other total flooding systems, such as gaseous agents.

At the same time, the report concludes that the *limitations* of water mist are associated with difficulties extinguishing small shielded or obstructed fires, due to the severely limited behaviour of the water mist as a gas. This behavioural limitation is associated with high-mist fallout rates due to gravity that tend to reduce the mist concentration significantly in areas away from the nozzle spray patterns.

Finally, the report states that if the fire size is above the critical value – or *critical fire size* – dictated by the conditions in the compartment (i.e. primarily a function of the ventilation conditions in the space), even if shielded, the fire can still be extinguished without any mist reaching the fire. The extinguishment of these fires is the result of a reduction in oxygen concentration in the space caused by the consumption of oxygen by the fire and a dilution of oxygen with saturated water vapour.

These same authors developed a model [9] (validated after these tests) to predict the effectiveness of water mist systems with obstructed fires where extinguishment primarily occurs as a result of oxygen consumption and dilution, neglecting the effects of the interaction of the mist with the flame. The steady-state temperatures and oxygen concentrations predicted could be used to determine the smallest fire (i.e. the critical fire size) that would sufficiently reduce the oxygen concentration to below the LOC of the fuel.

- ***A Review of Water Mist Fire Suppression Systems – Fundamental Studies***, Z. Liu, A. K. Kim, Journal of Fire Protection Engineering, Volume 10(3), 2000, pp. 32-50. [6]

  This paper provides a thorough review of the fundamental research in water mist fire suppression systems up to the year 2000. It includes a review of extinguishing mechanisms and the factors that influence the performance of water mist, such as spray characteristics, enclosure effects, dynamic mixing, the use of additives and methods of generating water mist.

  It summarises and concludes the following:

  - Water mist does not behave like a *true* gaseous agent in fire suppression.
  - The effectiveness of a water mist system in fire suppression is dependent on spray characteristics (the distribution of droplet sizes, flux density and spray dynamics) with respect to the fire scenario (shielding of the fuel, fire size and ventilation conditions).
  - Other factors, such as enclosure effect and the dynamic mixing created by the discharge of water mist, also affect the performance of water mist in fire suppression.

- ***Water Mist Fire Suppression using Cycling Discharges***, A. K. Kim, Z. Liu, J. Z. Su, Interflam Proceedings, 1999. [10]

  The test results published in this paper showed that the use of a cycling discharge – as opposed to a continuous water mist discharge – improved the efficacy of water mist in suppressing the fire, with a shorter extinguishing time and less water required.

  The tests showed that during the water mist off-cycle, the fire quickly recovered its strength and burned freely, resulting in the accumulation of a hot gas layer beneath the ceiling. The improvement of the efficacy using the cycling discharge was therefore attributed to:

- A higher overall evaporation rate as the spray passed through the hot gas layer during the on-cycle periods, resulting in more water vapour produced which in turn forced a faster depletion rate of oxygen in the compartment.

- A turbulent mixing during which water vapour and the combustion products from the hot gas layer were pushed downwards[iv], increasing the CO and CO_2 concentrations near the floor, diluting the fresh air entrainment and fuel vapour in the vicinity of the fire.

[iv] Same as with the previous footnote, this only applies with a vertical downwards water mist injection which is not the case in the 'safety fire-fighting technique' where the jet is directed parallel to the ceiling. In any case, the effect of O_2 depletion and/or high concentrations of CO, CO_2, and water vapour in the lower levels is ONLY desired with extinguishment as an objective, and NOT desired while applying the 'safety fire-fighting technique'.

6 Technical Summary on Water Mist/Spray Characteristics

The *extinguishing capacity* of water mist is the result of a complex interaction of [5]:

- fuel properties,
- enclosure effects,
- drop size distribution (DSD),
- spray flux density,
- spray momentum, and
- additives

To fully *characterise* a spray requires information about the following elements [4][6]:

- drop size distribution (DSD),
- cone angle,
- velocity of the discharge jet,
- mass flow rate, and
- spray momentum,

Drop size distribution (DSD): The term drop size distribution refers to the range of drop sizes contained in a representative sample of a spray or mist discharge. NFPA 750 has adopted the “cumulative percent volume” (CPV) versus “diameter” curve to represent the distribution of drop sizes in a water mist. The range of drop sizes can be fully described by characteristic parameters such as $Dv_{0.90}$ and $Dv_{0.50}$. The $Dv_{0.90}$ is the drop diameter at which 90% of the volume of a sample of the spray is contained in drops of that diameter or smaller. Similarly, $Dv_{0.50}$ is the volumetric mean drop diameter; that is, 50% of the volume of the spray is contained in drops less than that diameter.

Cone Angle: Commercially available water mist nozzles typically produce either 90° or 102° spray cones. Typically the sprays are solid cones, not hollow cone sprays like the typical fire-fighting nozzles.

Spray Velocity (V_w): Velocity is a vector quantity – it has both direction and magnitude. The directions of individual jets define the shape of the spray cone. The magnitude of the jet velocity is the velocity at which water emerges from a small orifice and begins to atomize. There is also a transfer of the velocity of the individual water particles to the surrounding air through drag effects. In a multi-jet nozzle (e.g. the typical fire-fighting nozzles), the drag effect of adjacent spray jets pulls surrounding air into the spray cone, adding to the *mass flux* of the spray cone. It is the combined velocity of the water droplets from all the jets and the air entrained in the flow that contributes to the spray *momentum* *(M_w)*, which dictates the overall impact of the spray on a fire plume.

Mass Discharge Rate ($\dot{m}_0$) & Mass Flow Rate ($\dot{m}_w$): The *mass discharge rate* ($\dot{m}_0$) of a nozzle is a function of water pressure and the total area of the orifice.

$$\dot{m}_0 = \frac{(m_{water} + m_{air})}{time} = \frac{(m_{wl} + m_{wa})}{time}\left[\frac{kg}{sec}\right]$$

Where m_{wl} and m_{wa} are mass of liquid water and mass of air entrained by mist, respectively.

Immediately after discharge, the *mass flow rate* of the spray ($\dot{m}_w$) will also include the mass of water vapour (m_{wv}) entrained by water spray. Therefore,

$$\dot{m}_w = \frac{(m_{wl} + m_{wv} + m_{wa})}{time}\left[\frac{kg}{sec}\right]$$

Spray momentum (M_w): *Spray momentum* refers to the *spray mass* (m_w), *spray velocity* (V_w) and its direction relative to the fire plume. The *spray momentum* (M_w) determines not only whether the water droplets can penetrate into the flame or reach the fuel surface, but it also determines the entrainment rate of surrounding air into the fire plume. The turbulence produced by the *spray momentum* mixes fine water droplets and water vapour into the combustion zone, which dilutes the oxygen and fuel vapour and increases the extinguishing efficiency of water mist in fire suppression. The *spray mass* (m_w) defined in the *momentum* of the spray, therefore, not only includes the mass of liquid water (m_{wl}) but also includes the mass of water vapour (m_{wv}) and mass of air entrained by water mist (m_{wa}). The *momentum* of the spray, M_w, can be expressed as follow:

$$M_w = (m_{wl} + m_{wv} + m_{wa}) \cdot V_w = m_w \cdot V_w \left[\frac{kg \cdot m}{sec}\right]$$

Where m_{wl}, m_{wv}, and m_{wa} are mass of liquid water, water vapour and air entrained by mist, respectively, and V_w is associated with the velocity vector of water mist, i.e. the combined velocity of the water droplets from all the jets and the air entrained in the flow.

In general, for a constant *mass discharge rate* ($\dot{m}_0$), increasing *spray velocity* (V_w) increases the air entrainment rate ($\dot{m}_{wa}$), which contributes to the *spray momentum* (M_w). Like *velocity*, *momentum* has both magnitude and direction – and its direction relative to the fire plume or fuel source has a bearing on its effectiveness.

Spray Flux Density (F_w): The ability of water mist to extinguish a fire depends only partly on having the appropriate (1) *drop size (DSD)* and (2) *spray velocity (V_w).* It also requires that the (3) mass of water spray that interacts with the fire be sufficient to absorb a critical portion of the heat given off by the fire (see *momentum* definition in this Section). *Spray flux density* refers to the amount of water spray in a unit volume – expressed in volume units of (Lpm/m^3) – or, in a more practical way to measure it, applied to a unit area expressed as (Lpm/m^2). It is, therefore, an important characteristic of water mist for fire suppression systems.

$$F_w = \frac{\dot{m}_w}{A} = \frac{(\dot{m}_{wl} + \dot{m}_{wv} + \dot{m}_{wa})}{area}\left[\frac{kg}{s \cdot m^2} = \frac{lpm}{m^2}\right]$$

Where $\dot{m}_w$ is the *mass flow rate* of the spray, and $\dot{m}_{wl}$ $\dot{m}_{wv}$ $\dot{m}_{wa}$ are mass flow rate of liquid water, water vapour and air entrainment rate by mist, respectively.

On a *compartmental scale*, the increase in the *spray flux density* will reduce the compartment temperature but will have little effect on the oxygen concentrations in the compartment.

On a *localized scale*, however, the fire is extinguished only when water sprays achieve a minimum flux density. Without sufficient flux density of water sprays to remove a certain amount of heat from a fire or to cool the fuel below its fire point, the fire can sustain itself by maintaining high flame temperature and high fuel temperature.

It is important to add that the *spray flux density* can also be obtained from the following:

$$F_w = \rho_w V_w = \left(\frac{m_w}{volume}\right) V_w = \frac{\dot{m}_w}{A}$$

Where ρ_w is the *spray density* and V_w the *spray velocity*, for what the *spray flux density* sometimes is referred as *spray momentum density* (i.e., density * velocity).

7 Programme of work – Implementation

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

- WP1. Literature review, fire-fighting guidance review, and theoretical research.
- WP2. Experimental investigation using existing small-scale (elongated) apparatus to investigate the effect of water mist application on the conditions in the compartment.
- WP3. Analysis of the results and elaboration of clear correlations which could be used in fire brigade guidance documents. These correlations would need to be validated in full-scale fire brigade exercises which are beyond the scope of the proposed project.
- WP4. Disseminate information through publications and directly to the fire brigades and related organisations.

7.1 WP1 Outcome

7.1.1 Summary of Findings

The following list summarises the most relevant theoretical and experimental research findings to date related to water mist application and the hypothetical best way to extract the thermal energy from a compartment fire, ultimate goal of the *gas cooling technique.*

a. The heat transfer modes between water spray droplets and a hot smoke layer are convective heat loss (until the droplets reach the boiling point) and evaporation heat loss (thereafter). The former is greater than the latter.

b. Only droplets with a diameter < 0.5 mm evaporate.

c. The total heat absorbed by the water is inversely proportional to the droplet diameter, and directly proportional to the smoke layer thickness the droplets travel through.

d. The *primary* mechanisms of extinguishment by water sprays are: (1) heat extraction (cooling), (2) Oxygen displacement (or *steam inerting*, and further depletion), and (3) radiation attenuation (or radiant heat blocking). The *secondary* mechanisms of extinguishment are: (4) vapour–air mixture dilution, and (5) kinetic effects at the molecular level.

e. Regarding *d*(1), compared with coarser sprays, finely divided water sprays enhance the speed at which the spray extracts heat from the hot gases and flame. Reducing the drop size increases the surface area of the water mass and thereby increases the rate of heat transfer.

f. Regarding *d*(2), on the *localised* scale, the volumetric expansion of the water droplets when they are converted to the vapour phase can disrupt the entrainment of air into the burning smoke layer extinguishing it temporarily. On a *compartmental* scale, the production of steam resulting from the water spray interaction with the flames, hot burning upper layer gas mixture, and/or hot surfaces, can significantly reduce the oxygen concentration in the enclosure, extinguishing it if the concentration falls below the LOC (Limiting Oxygen Concentration).

g. Regarding *d*(4), on the localised scale, the injection of water spray into the burning gas mixture can push the fuel concentration below the LFL (Lower Flammability Limit) ceasing the burning locally.

h. Regarding *d*(3), lowering the flame temperature reduces the radiation feedback. Also, water vapour in the air acts as a grey body radiator that absorbs radiant energy from the flames, hot upper layer, walls, etc. and reradiates it at a reduced intensity.

i. Enclosure effects maximize the benefits of *d*(1) gas cooling, *d*(2) oxygen depletion, and *d*(4) dilution. The degree of enclosure effects in fire suppression is mainly dependent on the fire size in relation to the compartment size.

j. The hot gases collecting in the upper layer of an enclosure are cooled rapidly by the first contact with the water mist typically resulting in an instantaneous volume reduction.

k. *Pulsing*, that is, the on-off action of water sprays also described as *cycling*, appears to lead to greater net evaporation and oxygen reduction than with steady injection. The improvement of the efficacy using cycling discharges is attributed to the faster depletion rate of oxygen in the compartment and the recurrent turbulent mixing created by cycling discharge.

l. A number of studies suggest – through plausible hypothesis – that water mist has the potential to mitigate explosion hazards.

m. A better mist dispersion has the potential to increase the system's performance.

7.1.2 Findings indirectly linked to the *Gas Cooling Technique*

This second summary list extracts the principles behind the previous list which are relevant in a direct or indirect way to the current research – i.e. those related to the practical application of the *gas cooling technique* – emphasising the methodology, compartment conditions, and characteristics that would increase the technique's efficiency.

- From *a*, *b*, and *c*, it can be shown that the ideal nozzle cone angle (which controls *momentum*) and pulse length (which controls *flux density*) are that which gives a water spray jet with as much penetration through the smoke layer as possible to maximise the heat absorption. The drop size distribution (DSD) should comprise drops small enough to maximise the evaporation but at the same time large enough to maximise penetration and thus the convective exchange. This means that the total heat extracted diminishes to either side of the ideal DSD following a hypothetical 'heat extraction vs. DSD' bell-shaped graph.

- With regard to *e* (or *d*(1)), it is implied that opposite velocity vectors of water spray and hot smoke flow result in the maximum degree of turbulent mixing in the collision zone, and hence improved cooling. This justifies the anti-whirl motion application of the water spray pulses in the *gas cooling technique*. This counter-motion maximises the convective heat exchange and further evaporation, maximising the total heat extraction from the gas phase. If sufficient heat is withdrawn, the gas-phase temperature of the flame can be dropped below that necessary to sustain the combustion reaction. This explains the temporary disappearance of the flames in the upper hot layer when the spray pulses in the *gas cooling technique* are correctly applied in a real compartment fire scenario.

- *f* & *g* further explain, through different mechanisms (i.e. localised displacement, depletion and dilution), the temporary disappearance of the flames in the upper hot layer when the spray pulses in the *gas cooling technique* are correctly applied in a real compartment fire scenario. When the water spray penetrates into the hot layer and is converted to vapour, the vaporizing water expands to 1,700 times its liquid volume. The volumetric expansion of the vaporizing water disrupts the entrainment of air into the flame (i.e. displaces the air in the vicinity of the evaporating drop – LOC) and dilutes the combustible mixture (gases + air) due to air and water entrainment into it (LFL). Further, if the air in the combustible mixture is saturated, the oxygen dilution by water spray increases with temperature at the 'expense' of a reduced tolerable oxygen concentration (i.e. increased depletion).

- With regard to *h* (*d*(3)), the statement that the cooling of the flame reduces the radiation (i.e. thermal feedback) to the fuel surface could be replaced, following the same rationale, to that the cooling of the upper gas layer reduces the radiation to the fire-fighters huddled below. Radiation attenuation is the result of the upper gas layer cooling and the increase in water vapour concentration between the later and the fire-fighters below. Lowering the smoke layer temperature – by extinction (oxygen displacement & further depletion) and/or dilution (see *f* & *g*) – reduces the radiation feedback to the fire-fighters. Also, water vapour in the air between the fire-fighters and the hot smoke layer acts as a grey body radiator that absorbs radiant energy from the latter and reradiates it to the former at a reduced intensity. In practical terms related to the *gas cooling technique* application (i.e. short pulses to provide a safe zone by cooling the gases in the immediate vicinity of the fire-fighting team – see Section 0), a given volume of water will provide a more efficient barrier against radiation if it is made up of very small droplets in a dense spray, than a dilute spray with larger droplets. As the concentration of drops with diameters smaller than 50 microns increases, the degree of attenuation of radiant heat increases.

- Regarding *i*, for fires in enclosures, it has been observed that larger fires increase the efficiency of evaporation ($d(1)$)– as opposed to smaller fires in the same volume – due to heat confinement in the enclosure. Also, *large* fires reduce the ambient oxygen concentration (oxygen depletion by consumption, $d(2)$) to the point that combustion efficiency will already be reduced, prior to introducing the water spray. In addition, higher gas temperatures can tolerate higher water vapour concentrations and therefore increase the oxygen dilution by water vapour ($d(4)$). So, enhanced enclosure effects combine the results of higher cooling capacity, higher vitiation/depletion, plus higher dilution capacity. To summarise, compartment effects are the first clue towards finding the g*as cooling technique's* applicability threshold in terms of compartment size vs. fire size (or related concepts), this project's main purpose. With regard to the technique, "large" and "small" fires are defined loosely in terms of whether the fire will affect the average temperature in the compartment before and during the application time of the technique. With "small" fires in the compartment, less heat and combustion products are released, so that the increase in gas temperature in the compartment is small prior to the application of the technique. The enclosure effect (i.e. heat entrapment + restricted ventilation) no longer has an important effect on the technique's performance.

- *j* explains the typical observation of the upper gas layer contracting immediately after applying the *gas cooling technique*, followed by the feeling of a fresher and cooler lower layer. This is because the rapid cooling results in an instantaneous volume reduction of the gases within the compartment that create a negative pressure that draws fresh air into it.

- Regarding *k*, in between the pulses injected by the fire-fighters, the fire regrows and the compartment temperature rises, allowing for more evaporation of lingering fine mist. This vapour can cool (gases/flames/solid fuel/other objects), but also dilute and/or displace the oxygen. The resurgent fire further reduces the oxygen concentration in the enclosure by consumption. The next injection of spray further cools and mixes the oxygen depleted gases. This reveals why the pulsing nature of the *gas cooling technique* is more efficient than a continuous spray application, which would in turn fill up the enclosure with unnecessary steam that increases the otherwise 'fresher' lower layer temperature where the fire-fighters (or any casualties) are located.

- In terms of *l*, this is related to a further linked research proposal's purpose of trying to find the minimum liquid water spray volume which would prevent a backdraught in the experimental configurations considered: "*Capability of the 'cutting-extinguishing' approach in under-ventilated fires*".

- The good mist dispersion referred in *m* could be paralleled to an appropriate application of the pulses – in quantity and distribution – in the *gas cooling technique* to enhance the technique's performance (e.g. and as a rule of thumb, 3 pulses in medium size compartments, 5 in large compartments, and 1 in corridors, as explained in Section 4.1).

7.2 WP2 Outcome

7.2.1 Aims & Objectives

The general *aim* of the experimental phase of the project was to assess the temperature reduction in the upper and lower layers of the compartment after water was applied as a spray. The *objectives* were to compare the effect different water volumes and different techniques (constant vs. pulsing) applications had on the overall compartment gas temperature.

7.2.2 Compartment

The small scale (elongated) experimental apparatus used in the previous study, see Figure 1, 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. In order to test theories and findings related to fires of different sizes in relation to the compartment size, the present project used variations to the fuel bed size and fuel load to give 3 'fire size vs. compartment size configuration' setups available to compare, as described below.

7.2.3 Water Spray Injection System

A water spray injection system as that shown in Figure 3 was used in the experiments. This system can spray water at a constant pressure, from pencil jet to a fine, hollow cone spray pattern, through a brass, adjustable nozzle.

Figure 3: 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.

7.2.4 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 PP pellets. The selection was based on ease of handling and setup, considering that this fuel produced in turn a robust repeatability for comparison and analysis. The optimum ratio of PP pellets to n-heptane was found – in the previous linked project – to be 2:1.

7.2.5 Data Measurement

The temperatures within the experimental compartment were recorded using three vertical thermocouple trees located at different positions along the compartment (see Figure 4), each with four K-type thermocouples at different heights.

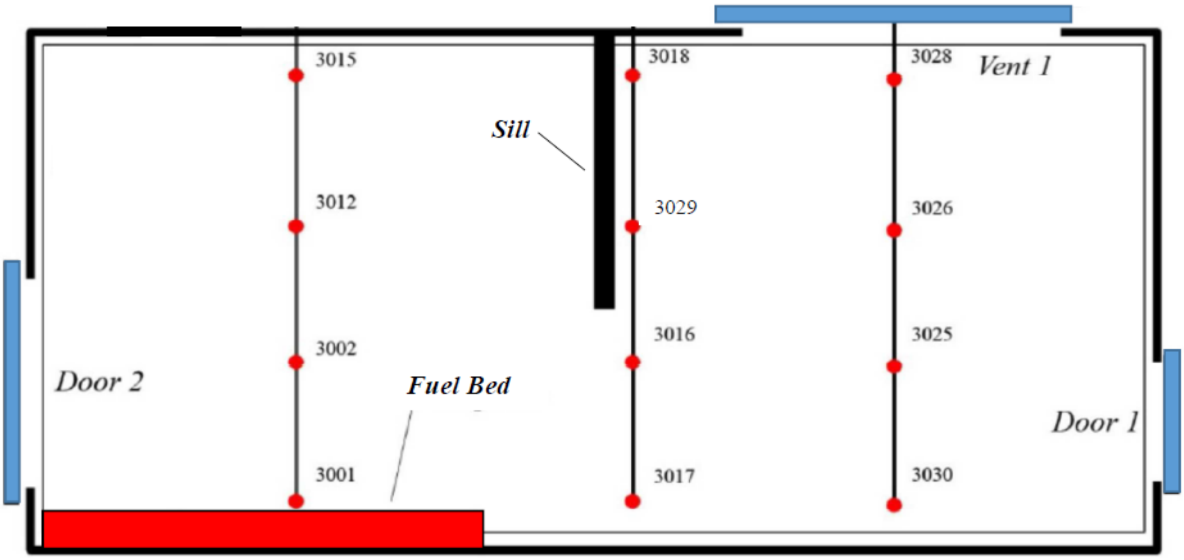

Figure 4: Compartment Side View Showing the Thermocouples Layout. The room to the right is Room 1 (or *Smoke Room*), while the room to the left is Room 2 (or *Fire Room*)

7.2.6 Preliminary Tests

Given that the efficiency of the *gas cooling technique* is directly linked to the enclosure effects, and that the degree of these effects is mainly dependent on the fire size in relation to the compartment size [5][6], it was decided to test varying the fire size while keeping the same compartment size.

Three trials were executed in the small–scale laboratory compartment prepared for WP2 (described in Section 2), with the following experimental variations in terms of the fire size:

Table 1: Fire Size Experimental Variations

FIRE SIZE CONFIGURATION	FIRE BED SIZE	FUEL LOAD
Trial 1	10 cm x 10 cm	200 gr PP + 100 ml C_7H_{16}
Trial 2	20 cm x 20 cm	400 gr PP + 200 ml C_7H_{16}
Trial 3	30 cm x 30 cm	800 gr PP + 400 ml C_7H_{16}

In all three experimental runs the fire was always located against the same corner in the same room (the *fire room*), the ventilation conditions were identical, and the water spray pulses injected into the *smoke room* were alike in terms of injection point, momentum, and flux density. The relevant resulting gas temperature history for each trial is displayed below:

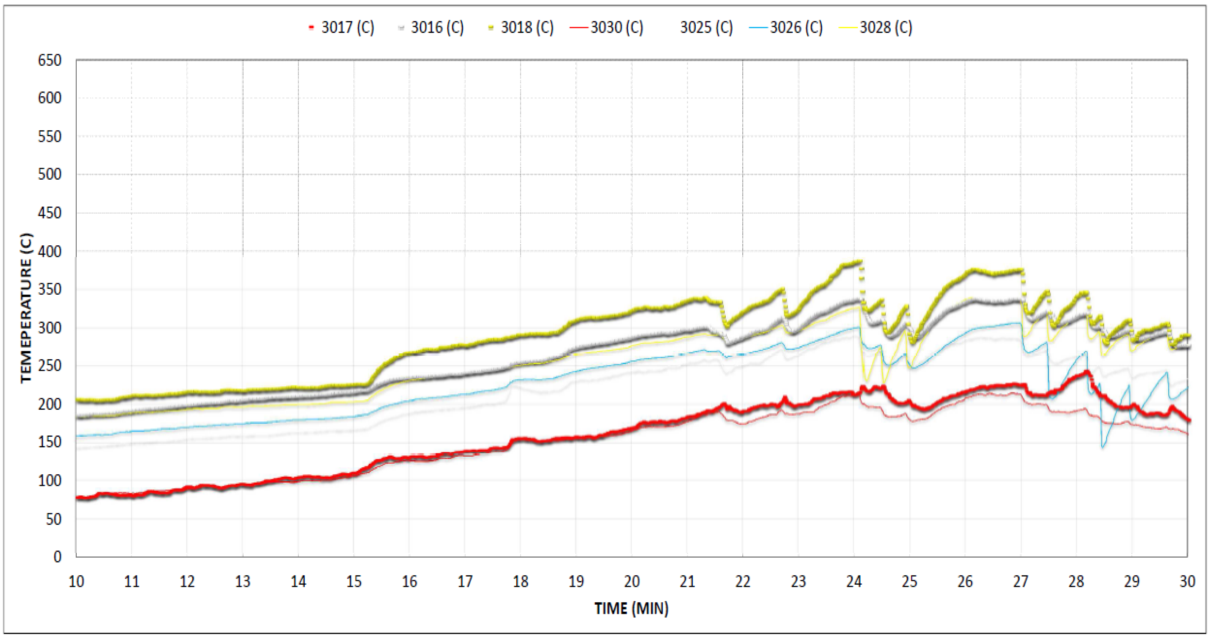

Figure 5: Gas Temperature History in the *Smoke Room* – Trial 1 Run

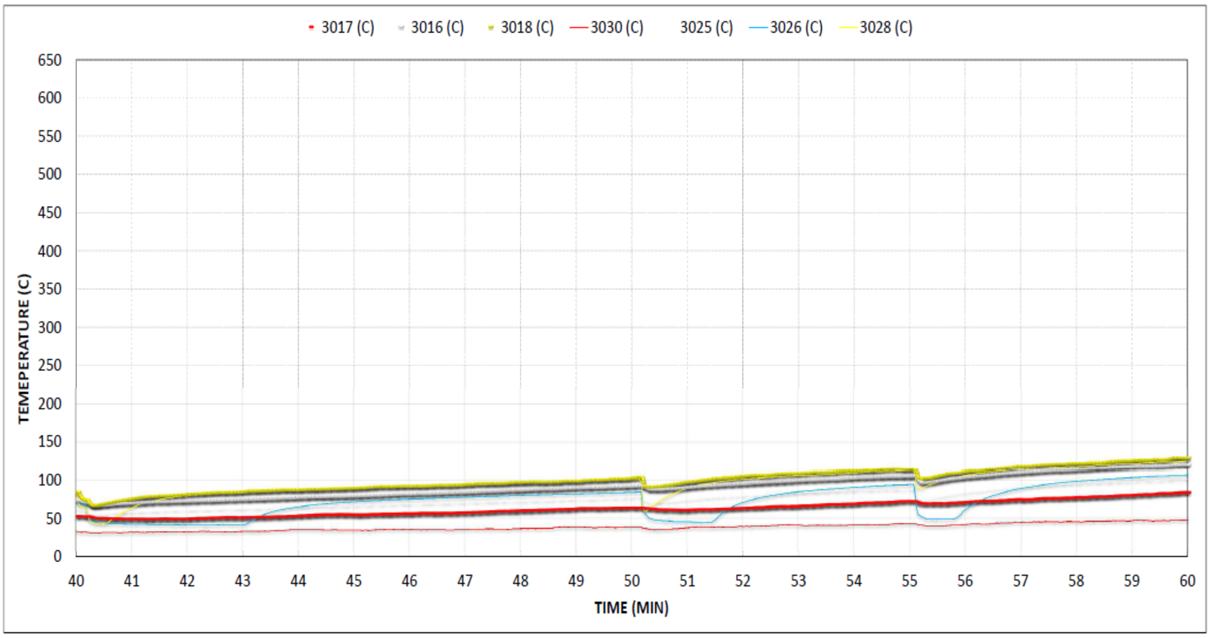

Figure 6: Gas Temperature History in the *Smoke Room* – Trial 2 Run

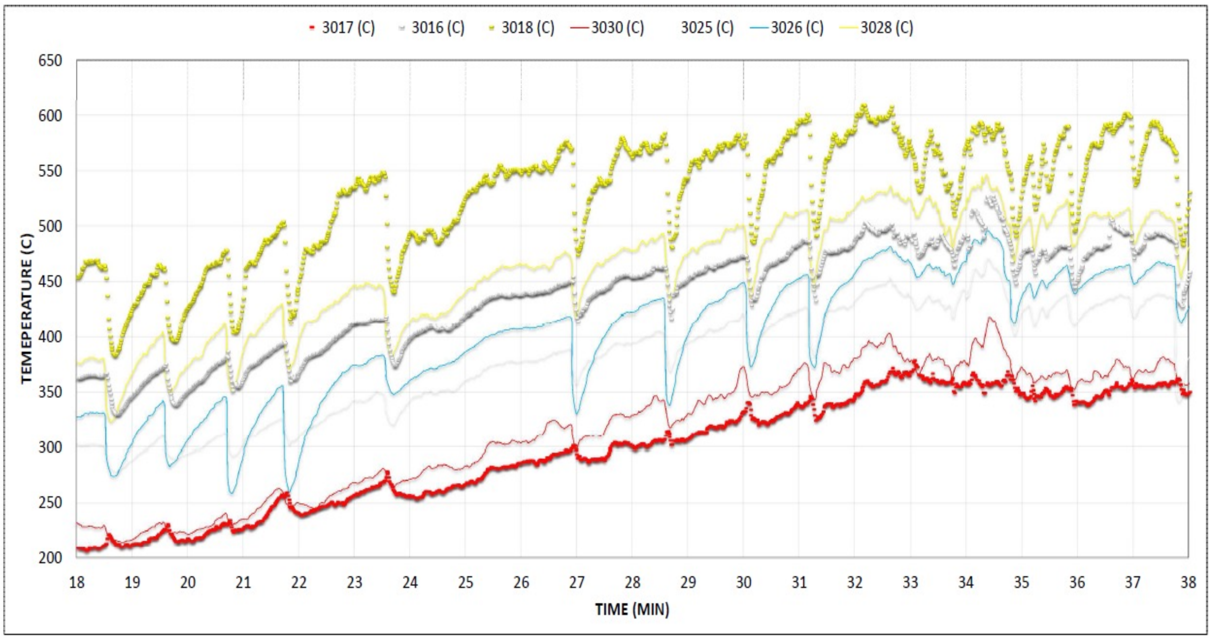

Figure 7: Gas Temperature History in the *Smoke Room* – Trial 3 Run

The first obvious observation in all three trials is that the negative temperature 'jumps' – i.e. the gas cooling effect immediately after directing a water spray pulse straight into the smoke layer – increase in the '*x*' direction, this is to say, with the room height.

In the third trial – that with the largest fire in relation to the compartment size – the negative temperature 'jumps' also increased in the '*z*' direction, this is to say, with the room depth. In trials 1 and 2 this increase was not observed, meaning that the horizontal gas temperature gradients in these cases where almost negligible, with a close to homogenous temperature field in the '*y-z'* (i.e. horizontal) plane.

Also, the third trial exhibited an increase in the negative temperature 'jumps' with time, i.e. as the fire was more prone to inundate the *smoke room*.

In summary, it was preliminarily observed that under these experimental conditions the gas cooling effect fundamentally increases as the overall compartment gas temperatures increase. It was therefore concluded that the varying fire size approach as a means to reproduce relative 'large' vs. 'small' fires with respect to a given compartment size and ventilation layout, was an adequate experimental path to assess the effectiveness of the *gas cooling technique* in a reduced laboratory scale.

7.2.7 Final Tests

After the preliminary observations and conclusions of relative 'large' vs. 'small' fires, three experimental fire size configurations where therefore selected as small, medium, and large, in relation to the fixed experimental compartment size, as follows:

Table 2: Fire Size Configuration

FIRE SIZE CONFIGURATION	FIRE BED SIZE	FUEL LOAD
Small	20 cm x 20 cm	200 gr PP + 100 ml C_7H_{16}
Medium	20 cm x 20 cm	400 gr PP + 200 ml C_7H_{16}
Large	30 cm x 30 cm	600 gr PP + 300 ml C_7H_{16}

The fire bed size and fuel load of the different fire configurations were selected in a way such so that, combined with the actual fixed compartment and ventilation opening size, would give increasing enclosure effects; i.e. higher vitiation plus increasing energy outputs, reflected in higher average gas temperatures in the *smoke room*.

As stated in section 7.1.2, compartment effects are the first clue towards finding the *gas cooling technique's* effectiveness and applicability threshold. A 'smaller' fire in the compartment releases less heat and combustion products, so that the increase in the average gas temperatures in the *smoke room* and the vitiation are comparatively smaller – prior to the application of the water spray – than with a 'medium' or 'large' fire. The enclosure effect (i.e., heat entrapment + restricted ventilation) has an important effect on the *gas cooling technique*'s performance.

The following two subsections describe the experimental procedure adopted and results obtained, respectively, for all the tests ran.

7.2.7.1 Experimental Procedure

The experimental procedure was pointed towards controlling as much as realistically possible the spray *momentum* and *flux density* (refer to section 6).

To this extent, the water sprayer was pressurised to between 4 and 5 bars, and the spray pressure control module set to give a constant output *pressure* of 4 bars. As a result, the magnitude of the jet *velocity*, i.e., the velocity at which water emerges from the nozzle, was set constant. In addition, the adjustable spray nozzle cone and orifice were set to a constant angle and opening, respectively, so that the nozzle's *mass discharge rate*, i.e. the mass of liquid water and mass of air entrained by the spray – a function of the water pressure and the total area of the orifice – was also set to a constant value. This, therefore, resulted in a fairly constant spray *momentum*.

Two experimental procedures were designed to compare the effects of varying *spray flux densities* which, in a practical way, refers to the amount of water spray per unit area (Lpm/m^2). To this extent, the ***first*** experimental procedure compared the effects increasing amounts of water spray injected – by means of varying duration of constant applications – had on the hot gas layer temperature drop as the fire evolved, while the ***second*** experimental procedure compared the effects equivalent amounts of water spray injected – by means of constant vs. pulsing techniques – had on said layer.

In the ***first*** experimental procedure, four distinctive constant spray injections (i.e. varying application durations and thus *spray flux densities*) were applied in increasing sequence from a fixed location – left side of door 1 – at different fire stages as the fire evolved. The volumes of liquid water at ambient temperature and pressure injected during this set of experiments were measured and checked before each experiment as follows:

Table 3: Volume of liquid water at ambient temperature and pressure applied during the first experimental procedure

Application	Technique	Volume of liquid water @ T_{amb} & P_{amb}
1’	Constant application	10 ± 1 ml
2’’	Constant application	15 ± 1 ml
3’’’	Constant application	20 ± 1 ml
4’’’’	Constant application	25 ± 1 ml

During the ***second*** experimental procedure, constant water spray applications from a fixed location – left side of door 1 – were compared to equivalent (in terms of water volume) pulsing applications from the left, centre and/or right side of door 1 depending on the case, at different fire stages as the fire evolved. The volumes of liquid water at ambient temperature and pressure injected during this set of experiments were measured and checked before each experiment as follows:

Table 4: Volume of liquid water at ambient temperature and pressure applied during the second experimental procedure

Application	Technique	Volume of liquid water @ T_{amb} & P_{amb}
1 constant application	Constant application	20 ± 1 ml
2 equivalent short pulses (Left + Right)	Pulsing application	10 ml + 10 ml = 20 ± 1 ml
1 constant application	Constant application	30 ± 1 ml
3 equivalent short pulses (Left + Centre + Right)	Pulsing application	10 ml + 10 ml + 10 ml = 30 ± 1 ml

The results of these experimental procedures are presented in the following subsection.

7.2.7.2 Experimental Results

The upper gas layer temperatures in room 1 (or *smoke room*) were averaged over the duration of the fire – TC 3016, TC 3029, TC 3018, TC 3025, TC 3026, TC 3028 (refer to Figure 4) –and depicted in red in the graphs.

The blue line reproduces the temperature history of TC 3030 representing what could hypothetically be the location of the fire-fighting crew following a compartment entry procedure (refer to section 4.2.2). This should only be taken as a reduced-scale experimental reference given the fact that once inside the compartment, the fire-fighting team typically moves away from the door and closes it behind to restrict the flow of fresh air into the compartment and avoid further fire growth or extreme fire behaviours, what would of course have a strong impact on the average upper layer temperature and consequent downwards radiation to them.

Further, it is important to note that Welch *et al.* [11] pointed out that errors in local temperature measurements in – especially large – post-flashover fires are compromised by the uncertainty known as the *radiation error*. The authors explained that a thermocouple placed in a hot gas layer may receive a lower radiation than that implied by the local gas temperature due to the influence of remote and cool surroundings such as a cold layer giving, as a result, slightly lower recorded temperatures than the true gas temperature. Contrary, in the lower layer, a temperature higher than the real local gas temperature can often be measured due to the influence of radiation emanating from the flames and/or the hot gas layer in the compartment which can be 'seen' by the thermocouple.

In these experiments, the thermocouples readings were not corrected to account for the *radiation error* as this is irrelevant in the context of this study. This is due to the fact that in regards to the upper layer temperature, we are only interested on analysing the space average temperature jumps and not the actual local gas temperatures; and in what concerns to the lower layer temperature – more specifically at TC 3030 location – we are not interested on the gas temperatures but on the thermal impact the surroundings would have on a fire-fighter who would actually be influenced by the radiation emanating from the flames and upper hot layer 'seen' by his body. In this sense, the lower layer temperature readings affected by radiation are more realistic and accurate than if they were corrected discounting the radiation effects.

Exemplary and representative results of both experimental procedures are reproduced below.

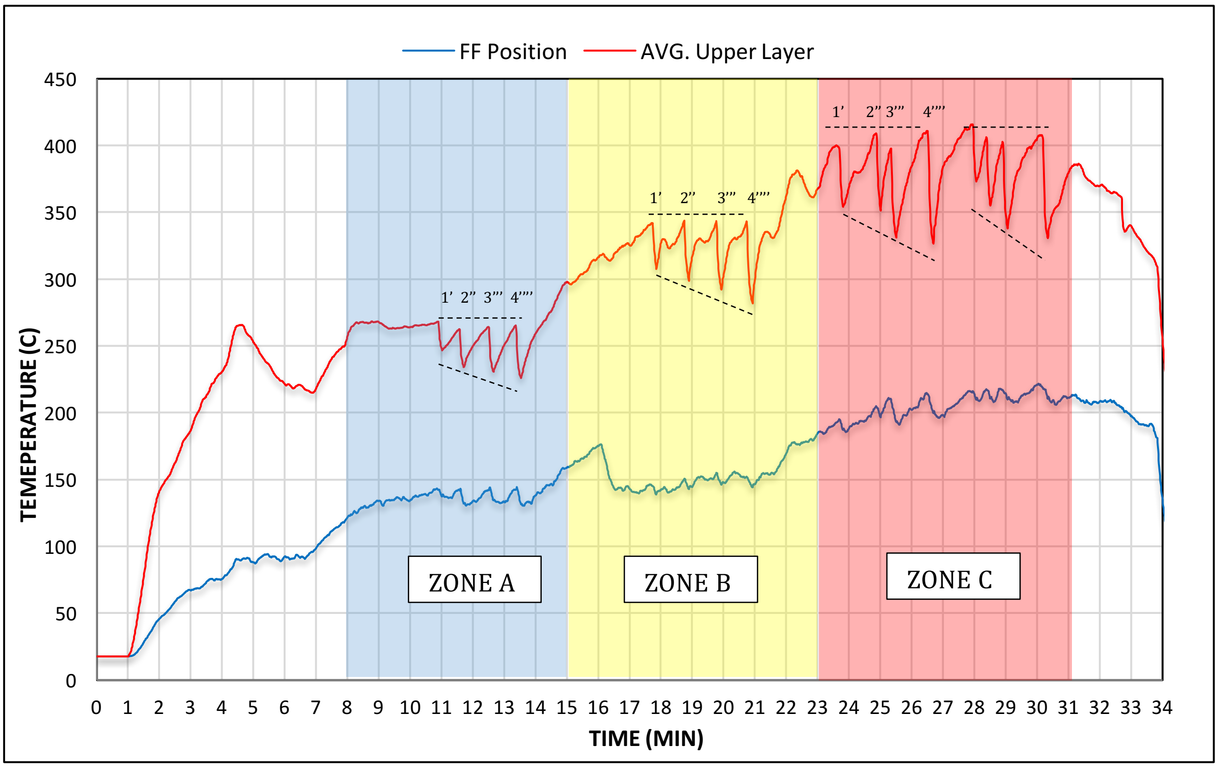

Figure 8: Room 1 (*smoke room*) average gas temperatures following the first experimental procedure [Run GCT 10]

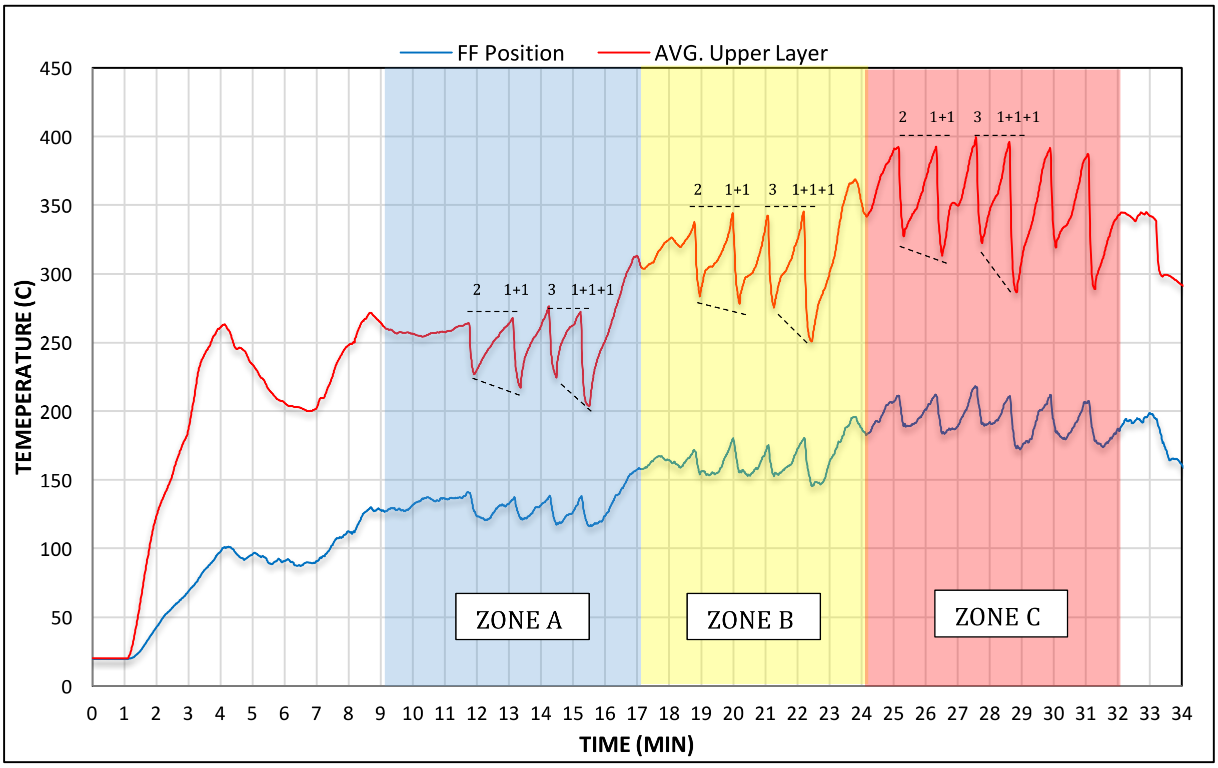

Figure 9: Room 1 (*smoke room*) average gas temperatures following the second experimental procedure [Run GCT B]

7.3 WP3 OUTCOME

The outcome of Work Package 3 (WP3) is directly linked to project's purpose (refer to section 2). Section 7.3.1 analyses the impact different application techniques have on the average upper layer temperature drop, while section 7.3.2 extracts a simple correlation between the water spray application and the average upper layer temperature drop as a function of the compartment size.

7.3.1 Experimental Analysis

Figure 8 contrasts the effect four increasingly longer constant spray injections (see Table 3) had on the average upper layer temperature in the *smoke room* when this was at three different average peak temperatures: ~250°C, ~350°C, and ~400°C. This figure is representative of the ***first*** experimental procedure.

On the other hand, Figure 9 contrasts the effect that constant water spray applications from a fixed location had to equivalent (in terms of water volume) pulsing applications directed in fanning motion (see Table 4) on the average upper layer temperature in the *smoke room* when this was at three different average peak temperatures: ~250°C, ~350°C, and ~400°C. This figure is representative of the ***second*** experimental procedure.

The results are clear and consistent, and are summarised under the following subjects:

Average temperature drop in the upper gas layer – Red Line

After analysing in details the results of both experimental procedure packages, it was clearly evidenced – as exemplified by both Figure 8 and Figure 9 – that the temperature drop in the upper gas layer is:

i. Proportional to the volume of water spray injected at ambient temperature and pressure. This is evidenced by the increasing negative jumps in each sequence of injection in zones A, B, or C in Figure 8.

ii. Proportional to the average upper layer temperature before injection. This is evidenced by the increasing negative jumps when comparing zones A vs. B vs. C in Figure 8 and Figure 9.

iii. More pronounced when this is injected in short pulses rather than all at once. This is evidenced by the increasing negative jumps within each zone A, B, or C in Figure 9.

iv. More pronounced with increasing quantity of pulses (3 vs. 2). This is evidenced by the increased temperature drop in zone C in Figure 9 when 3 pulses were applied against 2. This is related more to the efficiency of the overall distribution of water spray than to an increased volume of water applied, as manifested when comparing the different injection techniques (constant vs. pulsing) in equal average peak temperature zones, e.g. zone B from Figure 8 and Figure 9.

In what respects to *ii*, this highlights the concept of a minimum fire size with respect to the compartment size, for which the *gas cooling technique* is effective or otherwise ineffective, this project's main outcome. For this particular compartment size, zones A, B, and C from Figure 8 and Figure 9 could be regarded as relatively small, medium and large fires with respect to the compartment volume, in terms of achieving increasing enclosure effects, respectively, and therefore, improving the thermal conditions that will in turn improve the technique's efficiency.

Average temperature drop at the hypothetical location of the fire-fighting crew – Blue Line

Both representative figures show that within the cool lower layer, where the fire-fighters are hypothetically assumed to be located in a full-scale extrapolation scenario, the temperatures doesn't seem to be greatly affected by the longer water spray applications (Figure 8) nor by the difference of constant vs. pulsing techniques (Figure 9). In a reduced-scale scenario like this one, this was expected purely because of the experimental compartment size. Firstly, a small compartment does not allow to maximise the benefits of the pulsing technique; i.e. the anti-whirl motion (refer to section 4.1). And secondly, although radiation was the main heat transfer mode in these experiments – same as in a typical large-scale fully-developed fire – and this tends to increase the effectiveness of the water vapour acting as a grey body radiator (i.e., absorbs the radiant energy from the hot layer protecting the fire-fighters below) in a reduced-scale compartment like this one, it is believed that the water spray is carried away promptly out of the compartment and therefore the degree of attenuation of radiant heat decreases.

Water spray capacity to extract the thermal energy from a compartment fire

An interesting observation during these experiments, was the exceptional extinction capacity of the water spray that consistently put down the fire immediately after almost every spray injection. The fire, nevertheless, re-ignited after a few seconds in virtually every case.

In cellulosic materials the rate of decomposition into volatile gases that ultimately burn as flames depends on the heat supply to the material, and the primary source of this heat comes from the combustion of charcoal [12]. Contrary, in the case of liquid fuels and solid fuels decomposing without leaving behind combustible solid pyrolysis products the only source of energy required to maintain the preheating and vaporization is the heat evolved in the combustion of vapours. For liquid fuels, therefore, the thermal feedback from the flames and hot upper layer to the fuel surface is an essential feature of the burning process, as the rate of volatile production depends on it, or in other words, on the average compartment temperature. Additionally, the rate of volatile combustion depends on the rate of entrainment of air into the flame envelope.

In these experiments, the PP pellets melted reaching the liquid state and therefore burning as a liquid or pool fire. The water spray injected not only extracted heat from the hot upper layer but also displaced the oxygen from the flame envelope directly affecting both the volatile production and combustion, respectively, thus extinguishing momentarily the fire, which re-ignited after the water vapour was carried out of the compartment and the thermal feedback preheated the liquid fuel once more to its atmospheric boiling point.

This explains the repeated observation of extinguishing and re-ignition. A deeper study of these effects in cellulosic fires is an ideal starting point to understand the impact the so-called piercing-spray-lance technique might have on a typically furnished under-ventilated compartment fire, and ultimately on a potential backdraught situation. This examination is subject of a third research proposal recently put forward to the FSRTT "*Capability of the 'cutting-extinguishing' approach in under-ventilated fires*".

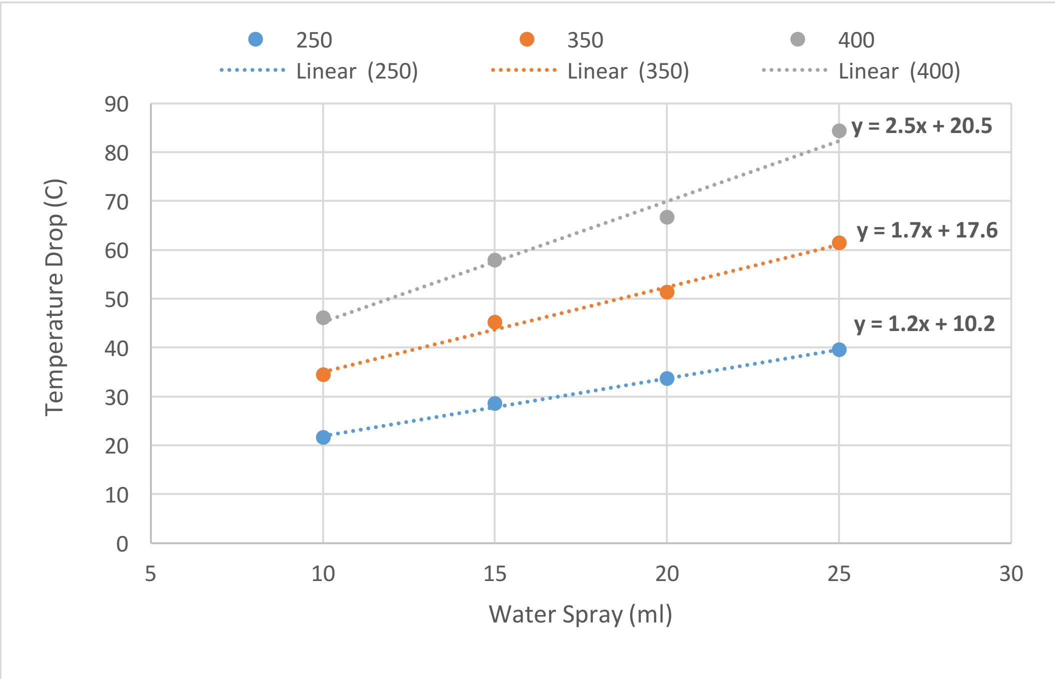

Figure 10: Temperature Drop tend lines as a function of Water Spray application and hot gas layer average temperature @ the time of application

7.3.2 Elaboration of Simple Correlations

It can be observed, and it was deduced from examination of Figure 9, that the average temperature drop in the hot layer is directly related not only to the amount of water spray injected, but also to the average hot layer temperature at the time of spray injection. The data from said figure was extracted to expose the trend lines of these correlations, and is presented in the graph above.

These three correlations (i.e. gradient equations) between the water spray application and the upper layer temperature drop for these specific average spray application temperatures (i.e. 250°C, 350°C and 400°C) are also function of the compartment size, or more specifically, of the hot layer volume.

Therefore, provided that the hot layer or *smoke* volume to water spray volume at liquid state (i.e. before injection) ratio is kept constant, these correlations could be extrapolated to make them available to large-scale compartments.

For example, assuming the smoke layer in the experimental box was 50% of its internal height, and that in a hypothetical real compartment it will be at the same proportion, if this large-scale compartment has the same dimensions for instance of a standard 42 feet container and the same ventilation configuration as the experimental box (i.e. a single vertical opening at one end), the temperature drop correlation for when the average upper layer temperature is about 350°C, could therefore be extracted from the following graph:

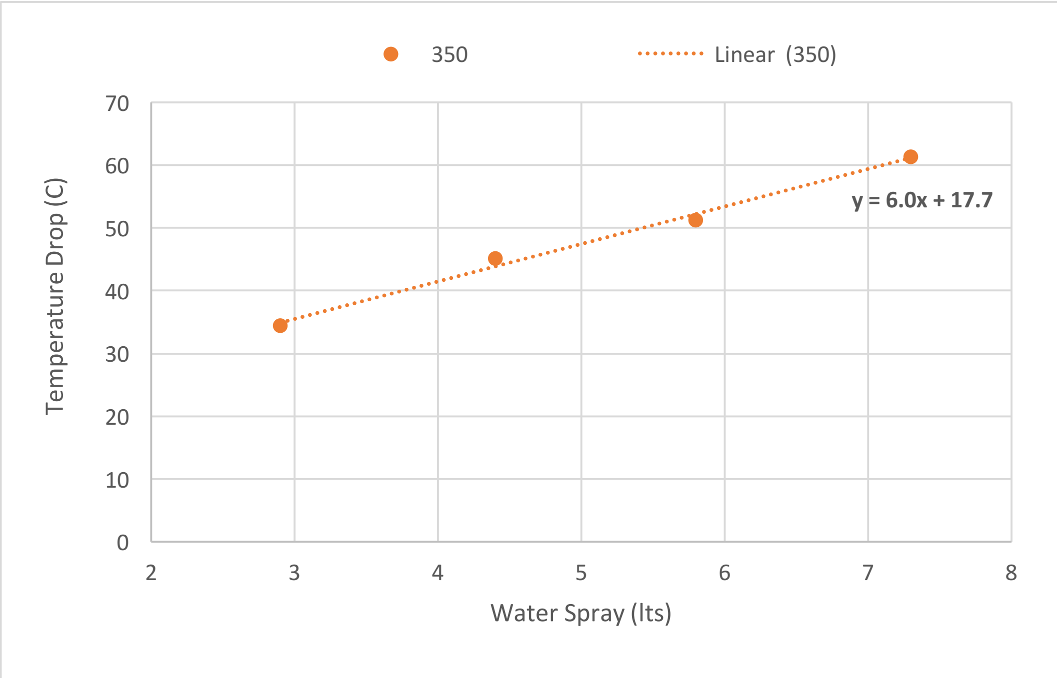

Figure 11: Example correlation extrapolated to a 13 feet container fire scenario with average upper gas layer temperatures of around 350°C.

This means that to drop the average hot layer temperature 50°C, i.e. to around 300°C, one should apply 50/9.1 = 5.5 litres of liquid water in spray in a single injection shot; to drop it 100°C, 11 litres of liquid water in spray are needed, and so forth.

These exemplified results could be validated against large-scale tests, although the validation must take into account the various variables in play that strongly influence the thermal energy extraction capacity of a given water spray from a compartment fire (refer to section 7.1.1).

Further, as it can also be observed and was deduced from examination of Figure 8 this time, the average temperature drop in the hot layer is directly related not only to the application technique (constant vs. pulsing) of water spray injected, but once more to the average hot layer temperature at the time of spray injection. Similarly, the data from this figure was extracted to expose the facts and tendency, and is presented in the following graph:

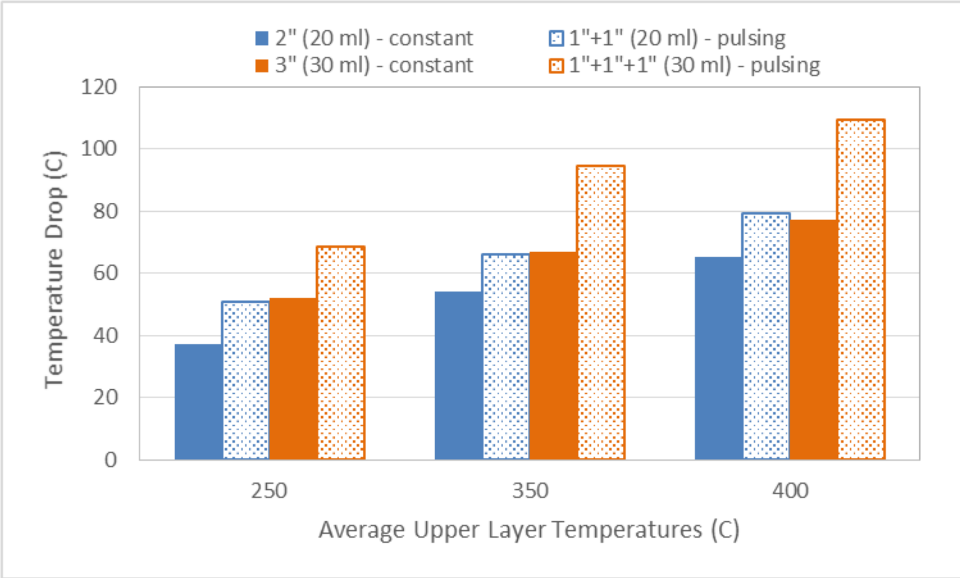

Figure 12: Temperature Drop as a function of Water Spray application technique (constant vs. pulsing) and hot gas layer average temperature @ the time of application

It is clearly apparent that the pulsing technique is significantly more efficient than the constant application technique – when applying the same amount of water – over the entire range of average upper layer temperatures tested. This graph also exposes – once more – the same evidence as all the previous graphs and figures that the temperature drop in the hot gas layer is proportional to the average upper layer temperature before water spray injection.

7.4 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 have been summarised into a presentation delivered at the BRE Trust Research Conference, Birmingham, November 2016. A presentation based on the previous FSRTT funded project was presented at the Re16 conference, also in Birmingham in November 2016. The results of this project will hopefully be presented at Re17 in 2017. In addition, a journal papers summarising the results are in preparation for future publication and dissemination.

In terms of the improvement of operational procedures related to the *gas cooling technique* – specifically, the general evidence outlined under section 7.1.2 in addition to WP3 findings (section 7.3) and the overall project conclusions (section 8) – this task is being shared with the fire brigades (London Fire Brigade + Scottish Fire and Rescue Services) through ongoing discussions and exchange of reports and specific training information.

8 PROJECT CONCLUSIONS

After the theoretical (section 7.1.2) and the experimental (section 7.3) findings, it can be concluded that it is effective to apply the *gas cooling technique* only when there is *sufficient* thermal energy within the upper gas layer in a given compartment. The thermal energy accumulated in the gas layer is a consequence of the relative size of the fire with respect to the compartment volume and ventilation conditions, which in turn govern the enclosure effects. It was certainly seen after the experiments that larger fires with respect to a constant compartment size and ventilation opening, achieved increasing enclosure effects which improved the overall thermal conditions that in turn enhanced the technique's efficiency.

The clue towards defining if there is *sufficient* thermal energy in a simple and universal way (i.e. non-dependable on the fire/compartment conditions) relies on the average upper layer temperature, and although there are indications after these experiments that the threshold is somewhere around 200°C (refer for example to Figure 5's temperature drops in contrast to all other figures) this should be validated in real-scale tests. Regardless where the actual threshold falls, it comes clear that very large compartments (e.g. a warehouse) admit in principle the conditions that diminish the *gas cooling technique* efficiency.

The minimum temperature threshold – quite simply measurable in real incidents by the attacking fire-fighting crew with a thermal camera – would be the first indication on when it is effective or otherwise ineffective to apply the *gas cooling technique*.

Once it is confirmed that the minimum average temperature threshold is attained – i.e., provided there is enough thermal energy within the upper gas layer in a given compartment – the difference between success or failure of the *gas cooling technique* in thermally managing the conditions in an enclosure, can be preliminary attributed – before full-scale tests can be ran – to variations in *spray momentum* and *spray flux density.*

In regards to the water *spray momentum*, this is determined by many factors [6]:

1. Water droplet mass and size transported into the ignited smoke layer
2. Water spray velocity and direction relative to the ignited smoke layer
3. Discharge pressure and cone angle
4. Ventilation conditions
5. Compartment geometry

The *spray momentum* will gradually decrease, as fine water droplets travel through the upper hot gas layer and the droplet velocity and size are reduced due to gravitational and drag forces on the droplets with the evaporation. The distance (X_{fall}) from the nozzle which water droplets can travel before falling in the air, is determined by *spray momentum* and discharge cone angle.

When water droplets fall in the air due to gravitational force, the maximum falling distance of the droplets is mainly controlled by droplet size and surrounding temperature, before they disappear into the hot gas due to the evaporation. Such maximum falling distance (X_{fall}), without considering the upward velocity produced by the fire, is given by:

$$X_{fall} = 2000 \frac{D_0 \, L \, \rho}{2 \, K_g \, \Delta T \, C_2}$$

Where D_0 is the droplet diameter, L is the latent heat of vaporization, ρ is the surrounding density, K_g is the thermal conductivity of the gas, ΔT is the temperature difference between the droplet and surroundings and C_2 is the coefficient.

The falling distances are significantly reduced with the droplet size reduction and with the increase in the surrounding temperature. Hence, depending on the penetration required (refer to section 4.1) larger/taller (i.e. more heat trapped) compartments would require narrower spray cones (i.e. larger droplets), while smaller/lower (i.e. less heat trapped) compartments would require wider spray cones (i.e. smaller droplets). Fine water sprays with too low momentum will not penetrate the strong ceiling jet to reach, for example, the back of the compartment, resulting in failure of the technique.

To avoid having the spray (and the water vapour) carried away by the ceiling jet, the momentum of the spray must be at least equal in magnitude, and opposite in direction, to the momentum of the ceiling jet. This relationship is given by:

$$M_{wx} \geq M_{jx}$$

Where M_{wx} and M_{jx} are the 'x' (i.e. horizontal) components of water spray and ceiling jet momentums, respectively.

The ceiling jet momentum, M_j, can be expressed as follows:

$$M_j = \left(m_{jp} + m_{jg} + m_{ja}\right) V_j \; \left[\frac{kg \cdot m}{sec}\right]$$

Where m_{jp}, m_{jg}, and m_{ja} are mass of combustion solid products contained in ceiling jet, mas of ceiling jet gases, and mass of air entrained by the ceiling jet, respectively, and V_j is associated to the velocity vector of the ceiling jet.

In regards to the water *spray flux density*, on a *localized scale*, the fire in the smoke layer will be extinguished only when the water spray pulses achieve a minimum flux density. Without sufficient flux density of water spray pulses to remove a certain amount of heat from a burning smoke layer cooling the fuel mixture below its fire point, the fire at ceiling level can sustain itself by maintaining high flame temperature and a non-directly-affected high fuel bed temperature.

In summary, the more control that can be exercised over *momentum* – by means of adjusting the nozzle cone – and over the *flux density* – by means of adjusting the quantity and length of each spray pulse application – the greater will be the ability to control water requirements and overall technique reliability.

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