University of Ulster

Faculty of Art, Design and the Built Environment

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Assessment Of Fire Suppression Capabilities Of Water Mist

- Fighting Compartment Fires with the Cutting Extinguisher –

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Abstract

The introduction of water mist used as an extinguishing agent by fire fighters and operated from outside of the enclosed fire room is a revolution that started in the last decade. More than a complement to traditional fire fighting, the only hand held lance capable of such results is named the Cutting Extinguisher.

Its recent development raised the interest of rescue services and fire engineers, conducting researchers to the first studies of the nozzle characteristics. However, many points regarding the abilities of the Cutting Extinguisher remain unexplored as yet. Some experiments were conducted for water mist measurement, fire tackling time and structural member drilling effectiveness, but there are still a number of unexplored parts in the literature, especially about the behaviour of water mist within the involved volume, and the variations of its capabilities related to the type, geometry and ventilation factor of the fire.

This report has been written with the aim of answering a part of these remaining questions, as well as studying further on some induced effects of the introduction of water mist in an enclosure.
It is based on the analysis of a series of full scale experiments, carried out in a compartment of 60 m^3. Over a period of three weeks, 25 tests were conducted, in a situation without fire, and 8 real burnings were achieved, involving the variation of both fire and extinguishing scenarios on the basis of three main parameters which were: the change of fuel surface, opening area, and water flow rate. The cold trials concerned the recording of the amount of water distribution per unit time, regarding the position of the mouthpiece, and visible behaviour of the mist, thanks to visual and video observation. The fire measurements were conducted thanks to instrumentation of the studied compartment by a volumetric meshing of 99 thermocouples, combined with heat flux, pressure and video recording.

The data analysis presents the results of findings in terms of water mist calibration, spray pattern, shaping and volumetric displacement, as well as concerning the flame blowing ability, cooling effectiveness, dependence on the studied parameters and induced consequences of the extinguishment.

Abbreviations

BA team	Fire Fighting Team equipped with Breathing Apparatus (sometimes called Smoke Divers)
CCS	ColdCut Systems AB, Swedish company manufacturing the Cutting Extinguisher
CEC	Cutting Extinguishing Concept
CFR	Critical Flow Rate
EDSP68	Ecole Des Sapeurs Pompiers du Haut-Rhin (Haut-Rhin Fire-fighting Training School)
FGI	Fire Gas Ignition
HRR	Heat Release Rate
LPG	Liquefied Petroleum Gas
MSB	Swedish Civil Contingencies Agency (Previously SRSA)
PPE	Personal Protective Equipment
SDIS	Service Départemental d'Incendie et de Secours (Fire Service)
SGE	Smoke Gas Explosion
SRSA	Swedish Rescue Services Agency
TC	Thermocouples

Declaration

Introduction

How can we fight compartment fires?

Two key concepts are present in this question. They both underline major issues of concern, firstly about the extinguishing agent which has to be used, and secondly on the way of using it, or in other words the fighting method chosen.
Today, even if prevention and automatic suppression systems are responsible for a constantly growing part of fire avoidance, it remains necessary for society to stay under the protection of Emergency Rescue Services, providing the essential human actions in order to fight fires. Because of the growing risks associated with fighting compartment fires, involving penetration into the burning building according to traditional methods, there is a constant need for technical and tactical development in terms of means of response.
The direction taken by these evolutions is made in the way of increasing safety, but also the efficiency of extinguishment, and reducing the collateral damage as well as the operating costs of Fire Services.

In terms of efficiency improvement and reduction of collateral damage, water mist finds an increasing place as an extinguishing agent. It was experimented with first as an alternative to Halon, and then developed and extended in recent years as a fixed active fire control system, for building protection. Since the use of water as a fine spray of atomised droplets is limited by the difficulty of developing general design rules, there is a need to conduct a study for each specific mist against certain scenarios. However, if it is properly designed, the capabilities of water mist as a fire suppressant are excellent. Thus, despite the complexity of water mist production and calibration, and regarding the requirement of adaptability to the various types and shapes of building encountered by fire fighters, some hand held nozzles were manufactured, and began to appear in the range of fire fighters' equipment.

And the remaining point: the question of increased safety.
Tackling a fire necessitates reaching it in a certain manner. Fixed protection systems, such as water sprinklers, foam generators or inert gas flooding agents have a fixed piping and heads network installed at strategic locations in the protected room. If fire fighters want to stay in a safe place, they should be able to project water from outside, through an opening. This is not always possible, and avoids the possibility of use of water mist, which does not have the required velocity and momentum to achieve sufficient travel distance into the involved volume. The common method used to extinguish indoor fire consists of introducing a team of operators protected by breathing apparatus, into the involved compartment.
Aware of the benefits of using water mist, and the issue of protecting the operators by working from outside, the Swedish Civil Contingencies (MSB), previously Swedish Rescue Services Agency (SRSA), collaborating with fire fighters, researchers and industry, invented a hand held lance able to produce water mist, and introduce it into the fire compartment from outside. The Cutting Extinguisher was born.

High pressure, abrasive added to the water stream, and a tiny nozzle orifice are the parameters allowing the ability to pierce, drill or cut any sort of structural material, as well as to produce water mist. The Cutting Extinguisher is experiencing extensive development around the world over the last ten years and is attracting a growing interest. However, because of the induced revolution of both technical, operational and tactical changes generated by the use of the Cutting Extinguisher, its applications were only studied for some specific environments, or to determine some particular characteristics of the tool. Literature and knowledge on the Cutting Extinguisher is still quite poor and incomplete.

This unique nozzle, with its inimitable properties, has stimulated our interest concerning the fire suppression capabilities of the produced water mist.
We then decided to focus on the study of the efficiency, impacts and consequences of fighting compartment fires with the Cutting Extinguisher.
Due to the lack of general knowledge, our goal in this research is to generate data, concerning both the mist characteristics, and the extinguishing capabilities, or the induced impacts of its use in terms of safety. In order to do so, we defined a standard enclosure, which constituted the invariant structure housing all our studies. During a three week period, as many tests as possible were carried out in this compartment, involving both cold flux measurements and real burning scenarios. For the water mist, measurements we based on a volumetric recording of water amount per spraying time. And for the full scale fires, we instrumented the compartment in a three dimensional meshing of thermocouples, combined with pressure, heat flux and video recording.


Background
Fighting Compartment Fires
Water as an Extinguishing Agent
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History
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Background

Fire.
A fire is a fast flaming combustion process. Widely used for ages, in every sort of application. When an unexpected fire occurs, the consequences are dramatic.

Fighting compartment fires

According to insurance companies, France experiences more or less 100 000 house fires requiring fire brigade intervention per year, being responsible for more than 800 death per year and 10 000 victims. Fire also causes extensive damage to properties, with the insurance sector putting an estimated figure of 1.3 billion Euros every year. This aloan explains why it is important to prevent fire, and reduce by this way the number of fires. On the second hand, if a fire still starts, it is vital to tackle it at an early stage, taking the appropriate action.
This thesis is primarily to fire fighters. It is assumed that the reader has some sufficient understanding on how fire behaves in an enclosure, as well as some knowledge about traditional compartment fire fighting (with breathing apparatus team operating a penetration in the structure). The main purpose, then, is to provide a suggestion on how it is possible to extinguish a fire in a degraded situation. "degraded situation" means a fire that can have uncontrolled spread, posing a constant danger to the fire fighter. These situations are likely to occur in under ventilated fires, and are also named Rapid Fire Progress (RFP). Included in these definitions are terms widely used and heard in the world of fire safety, such as Backdraught (or Backdraft), Smoke Gas Explosion (SGE), Flashover, Rollover, Fire Gas Ignition (FGI), and so on. We could express these phenomenon's thanks to a simple figure showing temperature evolution in function of time, in a room subjected to a fire:

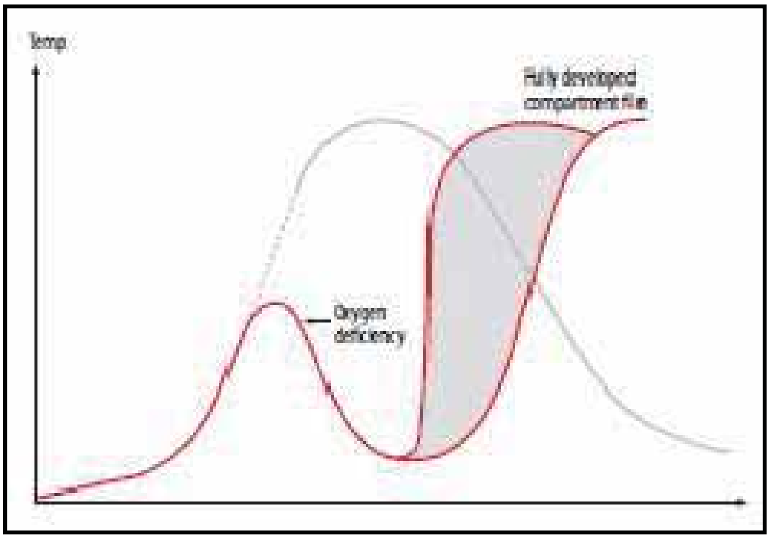


Figure 1. Time dependent fire growth curve (1)

They are included in the existing scenario between classical fire growth leading to flashover, and self extinction due to lack of oxygen. This area is called Grey Zone (or Grey Area).

To summarize, we have a simple problem: Fire is dangerous, and expensive in loss of life and properties, so it has to be prevented and fought. How can we fight it in the most reasonably efficient way?

Water as an extinguishing agent

Since humans control the fire, water has always been used. It is inexpensive and can be found fast everywhere. From the bucket to the actual fire fighting nozzle the principle remained always more or less the same: extinguishing the fire by water cooling. But if some tools are able to modify the way of spreading water, we could start to imagine some other ways of water application, and use it at its maximum efficiency. Used in a fog stream produced by a conventional fire fighting nozzle, it is assumed in the French National Reference Guide concerning the use of manual fire fighting nozzle that not more than 20 percent of the projected water is used, which means 80 percent on the floor and, damaging further the property.
Let us numerate the possible effects of water on a fire, which will enable us later to propose some methods of water application, inspired by the work Stefan Särdqvist and Göran Holmstedt (2) .

- Heat extraction. This constitutes the mainly considered effect of water on fire. As combustion is an exothermic chemical reaction, it releases energy as heat. Introducing cold water will cause absorption of this energy, while water is heated. The flames are then extinguished by cooling below the adiabatic flame temperature. As a reference, the specific heat capacity of liquid water at 15°C is about 4.18 kJ/kgK, which means that 1 kg of water at 15°C requires 4.18 kJ to be entirely warmed at 16°C, and so on. But its most powerful energy absorption is happening when water is changing from its liquid state to vapour: The vaporization of 1 kg of water requires 2260 kJ. Ideally taken, if we imagine a fire having 1 MW heat release rate (equal to 1 000 kJ/s HRR), we only would need to vaporize 0.5 kg of water within a second over this fire, in order to absorb all heat released. But being able to vaporize all this water within such a short time requires an optimal way of repartition and displacement of water molecules, which will be subject of a later topic.

- Oxygen depletion. The greatest extinguishing capacity of water is heat extraction. This aloan should be sufficient. However, there is more: As known, combustion being a redox chemical reaction, it requires, besides fuel and enough energy to sustain combustion, an oxidizer. The most common one is simply oxygen. From the fact that oxygen is a part of the gases in the composition of air at a level of 21 percent, we can assume that lowering its part below a certain point will end the chain reaction generated by combustion, and thereby extinguish the fire. Typically, we consider that below 12 percent no more combustion can be sustained. The role of water in this process is involving another of its physical property's when it is present in a gaseous phase: the volume change while temperature increases. This is a phenomenon explained by the so called "Perfect Gas Law" (or Ideal Gas Law) written as :

$$PV = nRT$$

  n ([mol] number of gas molecules) and R ([J/molK] general gas constant, 8.314) being constant for the same gas, we can see that Pressure and Volume depend on Temperature. So if

pressure remains the same, an increase in Temperature will generate an increase in Volume occupied by this gas.
Example:
Below 100 °C water remains liquid, so 1kg of water is approximately equal to 1 L.
And now with steam at 100 °C:

- 1 kg (55.56 mol) of water
- R = 8.314 J/molK
- P = 101325 Pa

At 100 °C we assume T = 373 K.

$$V_{100} = \frac{nRT}{P} = \frac{55.56 \times 8.314 \times 373}{101325} = 1.700\ m^3$$

At 100 °C, water being gaseous: 1kg of water is approximately equal to 1700 L.

At 500 °C we assume T = 873 K.

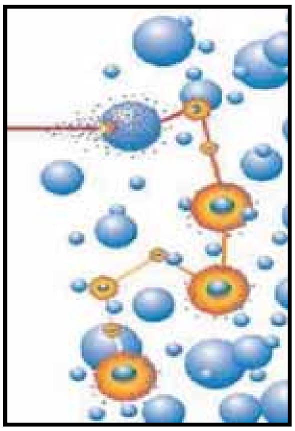
$$V_{100} = \frac{nRT}{P} = \frac{55.56 \times 8.314 \times 873}{101325} = 3.980\ m^3$$

At 500 °C, water being gaseous: 1kg of water is approximately equal to 3980 L.

Relating now the minimum required oxygen amount to steam expansion during extinguishing a fire in a structure, we can deduce that the vaporization will produce a mixing and by this way diluting of the air present in the enclosure, and reducing the content of oxygen. Consequently, flame cannot be sustained anymore, and fire is extinguished.

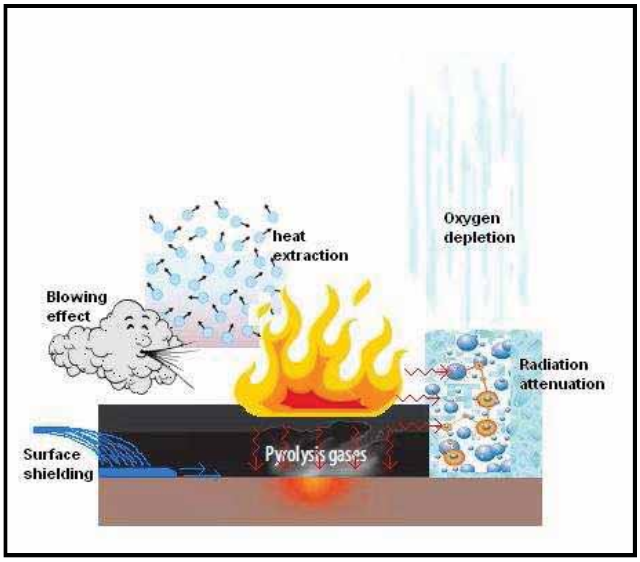
- Cooling effect/Surface shielding. “Cooling effect” means the direct action of water on the fuel. Since combustion is a gaseous reaction, the energy released by fire causes a gasification process of the fuel when heated. Damping the fuel will then cool it and stop this phenomenon also called pyrolysis. The fire has no more fuel, and is extinguished. This action requires an effective covering of surfaces, which again induces the way of spreading water.

- Radiation attenuation. Very rarely mentioned and taken into account in fire extinguishing, radiation attenuation, or even shielding, can also be done by water, depending on its repartition, droplet size and quenching. Radiation is responsible for pyrolysis, and it is also radiation which is responsible of fire evolution from a localized to a generalized fire (flashover) due to re-radiation from smoke and flame mattress on the ceiling, subjecting all the combustible items in the structure to dramatically high energy flows, which will involve them in the fire. Water, if used as a mist, can reduce this, or even block it entirely, depending on the thickness of the shield. To explain it briefly, we could represent radiation as a ray of energy (like a laser ray). Seen in a very small scale mist is a cluster of droplets, and when the ray hits a droplet, it loses energy in heating the drop and is diffracted, until



it reaches another droplet, and the same process occurs again and again until the ray is entirely absorbed (see picture beside).

- Blowing effect. Last of the known and significant process involved in fire extinguishing, blowing effect is not due directly to the water, but more to the momentum generated by the nozzle that sends water. Pressure in the pipe is converted into speed when water reaches the mouthpiece, which also generates an air entrainment. After a certain distance, varying with initial speed, spray pattern, and droplet size, it is the remaining air flow which carry the drops. And this air flow also has an influence; it disturbs the continuity of flame feeding by pyrolysis products, and the flame itself by scavenging. We still have sufficient energy to sustain combustion, but not at the same place where we have fuel… flame gets extinguished.



You may have understood it at the first instant; water is a very efficient extinguishing agent. It is actually about two times as efficient per unit weight as halon 1301, and almost as efficient as dry powder of high quality. It has been proven that the most powerful premixed flame can be extinguished with approximately 280 g/m^3 room volume, reduced to 140-190 for diffusion flames. The Critical Flow Rate (CFR, it is the lowest rate of water application necessary to achieve extinction, but with infinite amount of time available), as to it, is estimated to be less than 2.5 g/m^2s. Such values show us that the water amount is so insignificant here, that the efficiency of this astonishing extinguishing agent is not coming from flow rate, but from repartition, and I would add, from its displacement capacity.

Concentrating now for a brief moment on the water application methods, we could outline five major methods to tackle a fire, giving different effects on it: Spread droplets into the flames. The flames are extinguished by temperature lowering.

- Spread droplets into the flame. The fire is extinguished by flame cooling. The flames are gone out, but there is no action on pyrolysis, so fire may restart quickly, especially if there is a layer of charring material, allowing prompt re-ignition. But repeating this action of flame cooling will have, after a while, an impact: Reducing radiation will reduce the fuel gasification process, and cool the smoke, generating a better atmosphere, which also contributes to decreased re-radiation.
- Spread droplets in the smoke layer. Based on the principle of spraying droplets into the gaseous phase, this action will contract smoke and cool it, having more or less the same effect as the first method. It allows the fire fighters to approach the fire, and give them a better chance to tackle it.
- Inerting by steam generation. The benefit of water here takes into account its high volume expansion when changed to vapour, and heated over boiling point. This technique is achieved by painting hot surfaces with a nozzle, which will produce vaporization, and by this way oxygen depletion. The fire has no more oxygen, and the pyrolysis gases are mixed with inert

steam and combustion products, and the fire goes out. But there are some downsides making this technique seldom used: The structure has to be enclosed to contain the steam. This technique should not be used by fire fighter penetrating the space, since they will be subjected to this overheated expanding steam, and this is much harder to support than a dry atmosphere.

- Cool the burning fuel surface. Most commonly used technique; spreading water directly on the pyrolysing fuel will cool it, and stop gasification. The fire is immediately extinguished by lack of combustible gases, and water evaporates into steam, diluting combustion gases, and participating by inerting the volume.

- Shield the fuel surfaces not yet involved in the fire. More considered as a defensive strategy, this technique has no direct effect on the fire, it is just self consuming until it reaches the limit that does not pyrolyse, since it is covered by a shielding surface of water.

Five major principles of action and five known techniques of application... Water offers a wide range of extinguishing techniques. Just as it is true that there are some situations where one technique is much more preferable and efficient than another; it is preferable for fire fighter to have a versatile tool, capable of overcoming the majority of fires. This means, by extension, that water should be applied in a way offering the greatest use of most of its qualities. However, Heat extraction, Oxygen depletion, Surface shielding, Radiation attenuation, and Blowing effect requires suspension in the atmosphere, and then a volumetric repartition, it is not the case with surface shielding, where, as the name suggests we need an action on a surface, for covering.
This choice of surface or volumetric action determines the flow rate, and repartition of water. But as we only focus on compartment fires, it implicates we always have to take account of the gaseous phase. By logic, water should then be atomised in very small droplets, which will remain long enough in the atmosphere before reaching the floor; and should have a low flow rate. On the other hand, making the choice for surface covering generates a need of heavy drops having sufficient momentum to reach the pyrolysing material, and to moisten it sufficiently.
Having water sprayed into dense fog in the atmosphere is called water mist.

The water mist

We explained earlier why we choose to spread water into mist. But let us develop a little on the properties, and physics behind these small droplets and their extinguishing ability.

It is known that one of the most interesting properties of water in fire extinguishing is its ability to extract such a huge amount of heat when it is vaporized. It is also true that we need vaporization in order to have the desired oxygen depletion. So consequently, facilitating and increasing the extinguishing ability of water means facilitating water vaporization.
The process of endothermic heat transfer is based on the exchange boundary layer. Here the boundary layer is actually the droplet surface. A simple small calculation will highlight the importance of fine mist atomisation in order to increase the surface:

- Assuming a droplet being spherical, due to its surface tension more important than friction forces, we can use the following formulae:

$$V = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3$$

$$S = 4\pi\left(\frac{D}{2}\right)^2$$

- Let us take 1 g of water at ambient temperature, assumed to have a volume V_t of 1 cm^3, split into droplets of 1 mm diameter, it gives us:

$$V_d = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 = 0.52\ mm^3$$

$$\Leftrightarrow\ N = \frac{V_t}{V_d} = \frac{1000}{0.52} = 1910\ droplets$$

$$S_d = 4\pi\left(\frac{D}{2}\right)^2 = 3.14\ mm^2$$

$$\Leftrightarrow\ S_t = S_d \times N = 6000\ mm^2 = 0.006m^2$$

→ Splitting 1 cm^3 into droplets of 1 mm gives 1910 droplets, offering a total contact surface of 60 cm^2

- Let us now take the same volume V_t = 1 cm^3, but split into droplets of 0.1 mm (so 100 time smaller):

$$V_d = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 = 0.52\ \mu m^3$$

$$\Leftrightarrow\ N = \frac{V_t}{V_d} = \frac{1000000}{0.52} = 1909859\ droplets$$

$$S_d = 4\pi\left(\frac{D}{2}\right)^2 = 31.42\ \mu m^2$$

$$\Leftrightarrow\ S_t = S_d \times N = 60000000\ \mu m^2 = 0.6m^2$$

→ Splitting 1 cm^3 into droplets of 0.1 mm gives 1.9 million droplets, offering a total contact surface of 6000 cm^2 (0.6 m^2)

For the same volume of water, dividing by ten the size of the droplets allow an increase of contact surface to a factor of a hundred!

Moreover, still focusing on the size, but without considering the evaporation factor, it is also important to have small droplets in order to have a sufficient rate of attenuating shielding, as well as a long enough suspension time in the air. A droplet at its terminal velocity (when the gravitational force equals the frictional force) at room temperature has a speed which can be approximated as (according to the studies of Andersson P, and Holmstedt G, 1999 (3)

$$V_{term} = 31 \times D^2 \qquad 0 < D < 0.1\ mm$$
$$V_{term} = 4 \times D \qquad 0.1 < D < 1\ mm$$
$$V_{term} = 4.6 \times \sqrt{D} \qquad 1 < D < 4\ mm$$

Here, D is in mm and V_{term} in m/s

So, considering the same two droplet sizes of 1 and 0.1 mm diameter, let us estimate the falling speed:

- With D = 1 mm

$$V_{term} = 4 \times 1 = 4\, m/s$$
$$V_{term} = 4.6 \times \sqrt{D} = 4.6\, m/s$$

→A 1 mm droplet has about 4.3 m/s falling speed (average between 4.6 and 4 m/s)

- With D = 1 mm

$$V_{term} = 31 \times D^2 = 0.31\, m/s$$
$$V_{term} = 4 \times 0.1 = 0.4\, m/s$$

→A 0.1 mm droplet has about 0.355 m/s falling speed (average between 0.4 and 0.31 m/s)

In other terms, neglecting speed increase and vaporization, it means that, for a 2 m height ceiling, a 1 mm droplet will reach the ground within 0.5 s, whereas a 0.1 mm droplet will remain in the air during more than 5.5 s!

In order to have a bit deeper approach about the vaporization process of droplets, we have to consider the process of heat transfer that predominates. Since it is an interaction between gas and water, which can both be considered as fluids, it is called convection. In a desire to simplify, we consider that all the energy transferred is taken to vaporize the water, and neglect the energy required to heat up the water to boiling point. The heat transfer to a droplet is then:

$$\frac{dQ}{dt} = hS\Delta T = h\pi D^2 \Delta T$$

Where

1. $\frac{dQ}{dt}$ $[W]$ heat transfer
2. h $[W/m^2K]$ convective heat transfer coefficient
3. S $[m^2]$ surface of the droplet
4. ΔT $[K]$ difference between the temperature of surrounding gas and droplet

Now, the volume decrease of the droplet in function of time is expressed as:

$$\frac{dV}{dt} = \frac{4}{3 \times 8}\pi \frac{dD^3}{dt} = \frac{\pi}{2} D^2 \frac{dD}{dt}$$

So we can write the equation which represents the required energy to vaporize water:

$$-\frac{dQ}{dt} = H_v \rho \frac{dV}{dt} = H_v \rho \frac{\pi}{2} D^2 \frac{dD}{dt}$$

Where

5. $-\frac{dQ}{dt}$ $[W]$ heat required to vaporize
6. H_v $[kJ/kg]$ heat of vaporization = 2260 kJ/kg
7. ρ $[kg/m^3]$ density of water = 1000 kg/m^3
8. V $[m^3]$ volume of the droplet

And since the amount of heat transferred is equal to the amount required to vaporize, we can write the new expression:

$$-H_v \rho \frac{\pi}{2} D^2 \frac{dD}{dt} = h \pi D^2 \Delta T$$

Simplified:

$$\frac{dD}{dt} = \frac{2h\Delta T}{H_v \rho}$$

Before calculating our reference droplets life time and falling duration, we have to explain what is the convective heat transfer coefficient (h) and how to calculate it:
It depends on external flow properties:

- External flow velocity (v)
- External flow temperature (T)
- External flow heat conductivity (k), density (ρ), heat capacity or specific heat (c), kinematic viscosity (υ), dynamic viscosity (μ).

An empirical correlation can be written:

$$h = \frac{Nu \times k}{D}$$

where:

$$Nu = 2 + 0.6 \times Pr^{1/3} \times Re^{1/2}$$

(Applicable for *Pr* > 0.6; Blasius correlation for laminar flow)

1. *Nu* = The Nusselt Number (ratio of convective heat transfer rate to the diffusive heat transfer rate in the same fluid)
2. *Re* = The Reynolds number, (ratio of inertia to viscous forces)
3. *Pr* = The Prandtl number, (ratio of momentum diffusivity to thermal diffusivity)

For a sphere in cross flow, Prandtl and Reynolds number can be defined as follow:

$$Pr = \frac{c\mu}{k}$$

$$Re = \frac{vD}{\upsilon}$$

For our two examples, we meet two situations influencing convection. Droplets of 0.1 mm are so light that they are considered as behaving as a gas, and then are subjected to natural convection, whereas droplets of 1 mm size have a higher velocity, and therefore create a forced convection.

Thus, for a droplet of 1 mm diameter, we are in the case of forced convection.
Inspired by the researches of Stefan Särdqvist (4) case we can write the following equality (assuming the simplified equation):

$$Nu = 0.6 \times Pr^{1/3} \times Re^{1/2}$$

Since *Nu* is much greater than 2 that the value can be neglected), for life time estimation:

$$t_{life} = \frac{D_0 H_v \rho}{2kC\Delta T}$$

Which gives us the falling length before total evaporation:

$$l_{max} = \frac{v}{2} \times \left(\frac{D_0 H_v \rho}{2kC\Delta T}\right)$$

Where:

4. D_0 $[m]$ is the initial droplet diameter
5. C is a constant calculated as:

$$C = 0.6 \times \left(\frac{c\mu}{k}\right)^{1/3} \times \left(\frac{1}{\upsilon}\right)^{1/2} \times \sqrt{v}$$

Where:

6. c $[kJ/kgK]$ is the specific heat of the surrounding atmosphere
7. μ $[kg/ms]$ is the dynamic viscosity of the surrounding atmosphere
8. k $[W/mK]$ is the thermal conductivity coefficient of the surrounding atmosphere
9. υ $[m^2/s]$ is the kinematic viscosity of the surrounding atmosphere
10. v $[m/s]$ is the falling speed of the droplet

Let us assume now the travel of that droplet from ceiling to the ground, surrounded by a constant air temperature at 400 °C, having a dynamic viscosity of 3.25 x 10^{-5} kg/ms, a kinematic viscosity of 62.53 x 10^{-6} m^2/s, a specific heat of 1068 J/kgK, a thermal conductivity of 0.0515 W/mK, a water temperature of 100°C, and a falling speed of 4.3 m/s:

$$C = 0.6 \times \left(\frac{c\mu}{k}\right)^{1/3} \times \left(\frac{1}{\upsilon}\right)^{1/2} \times \sqrt{4.3}$$

$$C = 0.6 \times \left(\frac{1068 \times 3.25 \times 10^{-5}}{0.0515}\right)^{1/3} \times \left(\frac{1}{62.53 \times 10^{-6}}\right)^{1/2} \times \sqrt{4.3} = 229.9$$

$$t_{life} = \frac{D_0 H_v \rho}{2kC\Delta T} = \frac{0.001 \times 2260000 \times 1000}{2 \times 0.0515 \times 229.9 \times 300} = 318.1\ s$$

$$l_{max} = \frac{v}{2}\left(\frac{D_0 H_v \rho}{2kC\Delta T}\right) = \frac{4.3}{2} \times 203.7 = 683.9\ m$$

➔ A 1 mm diameter droplet has a life duration of 230 seconds and can travel 684 m in a 400°C surrounding atmosphere before being totally vaporized.

For a droplet of 0.1 mm we are in the case of natural convection:
In this case the Reynolds number is very small, and Nu is then very close to 2. The equation calculating life time (assuming then $h = 2k/D$) can therefore be written:

$$t_{life} = \frac{{D_0}^2 H_v \rho}{8k\Delta T}$$

Which gives us the falling length before total evaporation (considering $v = 31 \times D^2$):

$$l_{max} = \frac{v}{2} \times \left(\frac{{D_0}^2 H_v \rho}{8k\Delta T}\right)$$

Again, we now can calculate the travel of that droplet from ceiling to the ground, surrounded by a constant air temperature at 400 °C, having a dynamic viscosity of 3.25 x 10^{-5} kg/ms, a kinematic viscosity of 62.53 x 10^{-6} m^2/s, a specific heat of 1068 J/kgK, a thermal conductivity of 0.0515 W/mK, a water temperature of 100°C, and a falling speed of 0.355 m/s:

$$t_{life} = \frac{{D_0}^2 H_v \rho}{8k\Delta T} = \frac{0.0001^2 \times 2260000 \times 1000}{8 \times 0.0515 \times 300} = 0.183\ s$$

$$l_{max} = \frac{v}{2} \times \left(\frac{{D_0}^2 H_v \rho}{8k\Delta T}\right) = \frac{0.355}{2} \times 0.094 = 0.032\ m$$

➔ A 0.1 mm diameter droplet has a life duration of 0.18 seconds and can travel 3.2 cm in a 400°C surrounding atmosphere before being totally vaporized.

It appears here clearly that 1 mm droplets will, regardless of the height, the propelling speed, and the temperature, either hit the floor or worst a hot wall. This will either cause an inevitable waste of water, causing property damage, or get vaporized and produce steam, which is dangerous in case of intervention in the room with BA fire fighters.
Fine mist on the other hand is more likely to follow the air flows, and due to its small life duration, vaporize in the gaseous phase, instead of on a wall.

The work of P. Andersson and G. Holmstedt in 1999 (3) seems to confirm this hypothesis, in experimenting the trajectories for droplets of different sizes in an horizontal air stream directed towards a wall at 4 m/s: *"At 0.2 m from this, the air stream follows a circular path with a radius of 0.2 m. [...] no account is taken of gravity. In the figure, it is seen that all droplets with diameters above 20 µm will hit the wall due to inertia. In fig. 5, the same calculations are performed for the case where droplets and air move towards the wall at 0.5 m/s"*

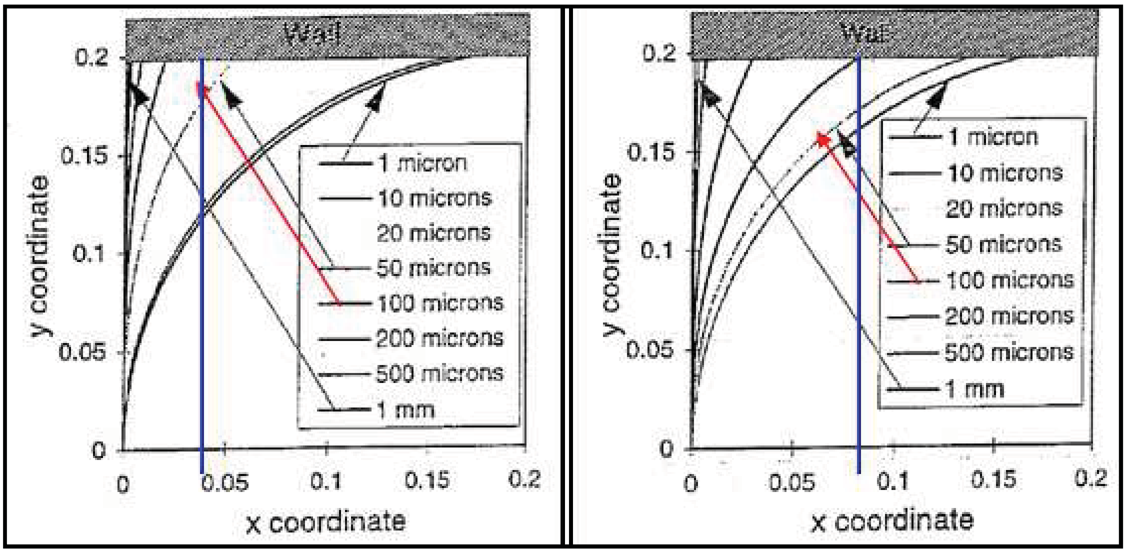


Figure 2. Trajectories for Droplets of Different Sizes in an Airflow of 4 and 0.5 m/s. (3)

For us, the main interest of this work is to compare the droplets of 1 and 0.1 mm. It is clear that, regardless of the speed of the air stream, the 1 mm droplets have a too high inertia, and will inevitably hit the walls. The 0.1 mm droplets, in the other hand are likely to strike the wall also, at 4 m/s, but with 0.5 m/s, the travel a distance of approximately 8 cm on the X axis before striking the wall. Considering now the case of a fire: Larger droplets will produce steam, without so efficient gas cooling effect, whereas smaller will have no other choice than vaporize in the volume, remembering their travel distance of 3.2 cm calculated in a 400°C environment.

If we imagine now an enclosure, with large and more or less regular air streams, as generated by the fresh air inflow, and hot gases outcome, added to the velocity of the fire plume (between 5 and 10 m/s) we could consider that water mist having a droplet mean diameter below 0.1 mm is having a full volumetric action, and is entering in the classification of total flooding agents.

In order to produce water mist, there are five known methods of atomising water today:

- Pneumatic atomisation. This process requires the use of compressed air or another sort of gas that has to strike the water vein at its outcome of the nozzle. The pressure required is generally quite low: around 10 bars and it is supposed to produce the finest droplets.
- Atomisation by gas expansion. This method also requires the use of compressed air or another sort of gas, but it is directly injected in the water vein in the pipe work. At the mouthpiece, the gas expands and helps to atomise water. This principle also produces very small droplets, and especially if the air flow is very important in comparison to the water flow.
- Mechanical atomisation. The water vein strikes a spreader plate located at the water outcome. Water splits into a spray, with coarse drops. It is very often used at low pressure ranges, and for systems like sprinklers. The geometry of the plate can vary, in order to produce different form of spray: flat shaped, with circular grooves, or helically grooved cone are the most common.
- Use of overheated water. Based on the temperature increase of water, over its boiling point, but under pressure to keep it in a liquid state, this technique produces atomisation when pressure has fallen to ambient conditions. At the mouthpiece of the nozzle, a part of the water is vaporized, generating a cloud composed of steam and fine droplets.

- Hydraulic atomisation. This process consists in projecting water through one or several nozzles of small diameter, having a shape determining the type of spray. Usually, hydraulic atomisation requires working at high pressure, with a low flow rate. At a certain distance from the nozzle, depending on several factors as well as the shape of the mouthpiece, the water jet disperses into a fine water mist. The higher the working pressure, the smaller the droplets produced. Pressures higher than 100 bars offer a fine water droplet comparable to the pneumatic atomisation process.

Considering the five methods to produce the desired water mist, and keeping in mind the need for easy handling required by fire fighters, we can reasonably only outline two techniques, which are Mechanical atomisation, and Hydraulic atomisation. However, as shown earlier, the finer the mist, the better it is to convince us to focus only on hydraulic atomisation.

The Cutting Extinguisher

History

There are only few fire fighting nozzles existing today, which are capable of producing the desired mist: fine enough to behave like a gas. And this number falls to only one tool, if we take into account the constraints of safety for the fire fighters. Because of the previously mentioned risks of burns due to overheated steam, and also because of the lack of protection by creating a protective water curtain, there is only one tool capable of doing it all

Figure 3. Hand held part of the nozzle, with two triggers; one for water and abrasive, the second only for water. Picture: Service communication SDIS68

This tool is named COBRA Cutting Extinguisher, and is manufactured by the ColdCut Systems Company, in Sweden. The COBRA Cutting Extinguisher is the result of combined work between the Swedish Rescue Services Agency, fire fighters, fire engineers and the industry. The first prototype of this nozzle emerged in 1997. The initial idea of the fire fighters and the Swedish Rescue Services Agency was to adapt a tool which was able to cut holes in the roofs ceiling coverings, in order to evacuate smoke and combustion gases from room fires. They wanted to avoid chain saws or grinders, which generate sparks, and may ignite the gases as they are coming out. They decided then to test water cutting, and it appeared that the water used to cut the opening was completely extinguishing the fire before the hole was finished. The experimental unit was called COBRA Cutting Extinguisher, whose aim was to drill a single small hole, and spray its water into a fine mist through the hole, , using the hydraulic atomisation properties. It is used more and more extensively around the world, four hundred units are in operation, in over thirty countries.

Specifications

The COBRA Cutting Extinguisher is a tool capable of extinguishing fires by perforating the compartment. Its normal working pressure is 300 bars, for a flow rate of 60 L/min (1L/s). In order to be able to drill every type of structural members, an abrasive powder is added (composed of iron oxide, aluminium oxide and manganese) at 4% of the water volume used and having a size included within the 0.3-0.8 diameter range. This mixture, at high pressure, forms a very concentrated water jet

when passing through a 2.3 mm diameter mouthpiece. The system is also able to introduce a foaming or wetting agent, in order to increase the surface shielding effect; but we will not take that into account in our study of the water mist produced.

Figure 4. The abrasive, calibrated at 0.3-0.8 diameter mm range

There is some consistent literature concerning the COBRA Cutting extinguisher, most of it dealing with tactical and operational uses, like the publications of Lars-Göran Bengtsson (1) and Stefan Särdqvist (4). But those which concentrate on the physical properties and the extinguishing capabilities are quite poor, or non-existent.
By stating the results of a research started last year, and a thorough investigation with the Swedish Rescue Services Agency, and Cold Cut Systems Company, we can identify five main reports published today, including three of them written in Swedish language.

State of Art

The first document, being the research and development report from the Swedish Rescue Services Agency was published in 2001 (The Cutting Extinguisher – concept and development (5)), and explains in depth *"how an entirely new fire extinguishing method was developed from an idea into a finished method"*. In addition to reporting the history of its birth, the document also contains the only completed scientific study on the theoretical calculations of extinguisher water (An Assessment of the Cutting Extinguisher's Capabilities and Limitations (6)), done by Professor Göran Holmstedt at the Lund University of Technology, in Sweden. Some experimental tests were also done, in order to compare the efficiency of the tool, with theoretical results. Unfortunately, as the report describes the first researches in order to calibrate the Cutting Extinguisher, it is based on some parameters which are no longer valid. Actually, the pressure and flow rate initially tested were at 200 bar and 46 L/min, which were not considered sufficient for cutting constructions of several layers of different materials. So one of the required changes *was "Increasing the starting pressure by approximately 100 bar gives the desired cutting capacity even where several layers are involved"* (Production of prototype/evaluation p. 15). And indeed, the first Cutting Extinguisher that was sold had a working pressure of 300 bar.
Based on Bernoulli's equations, it was stated that a working pressure of 200 bar, an in-pipe water velocity of 4 m/s, and an orifice diameter of 2.2 mm; the velocity of the jet at the mouthpiece would be 201 m/s. Deduced from experimental measurement, the coefficient of flow arising from contraction was found as 0.83. From these values, the flow rate could be deduced, and a value of 46 L/min was found.
In accordance with Newton's second law, the reaction force of the lance with the given pressure, coefficient of flow and nozzle orifice section, is 154 N. This was then confirmed by experiments, carried out at Revinge, where the value of 150 N was recorded.

Considering the distance for the water jet to split up, the work of Kuhn was used, giving some examples of required time for instability to develop, in function of the diameter of water jet. For a 2 mm water jet, the given time is 0.074 s, creating a distance of 14 m if the value of 200 m/s is taken. In reality, professor Göran Holmsted noted a break up distance of 5-6 metres; the jet having an inner core before this, and splitting completely up after this distance. The sizes of inner core and outer ring were summarized for some distances from the nozzle in the following table:

Table 1. The geometry of the jet.

Distance from nozzle in metres	0	1	4	7
Core diameter in millimeters	2[1]	15	60	-
Outer diameter, ring, in millimeters	2	100	400	1100

1. Based on orifice diameter 2.2, and coefficient of flow 0.83.

Table 1. Geometry of the jet (5)

It is noted that at the distance of 7 metres the water droplets moves at the same speed as the air sucked into the mist ring. We can then make the hypothesis that before this point, the jet is draining an air stream due to Venturi effect, and after the jet breaks up, the entrained air is then carrying the produced mist, and is pushed continuously by the new coming air, allowing for mist transportation.
Measurement of cutting power (measured in MN/m^2) and induced distances for user and people safety were also estimated, giving a cutting ability of every sort of material at point blank from the nozzle, an ability to penetrate chipboard at 2 metres and a safety distance of 7 metres.
Finally, regarding the extinguishing capabilities of the Cutting Extinguisher, the statement of an average volume droplet with diameter of about 0.1 mm is made, and the following data is shown:

Table 3. Water content in spray

Distance from nozzle, meter	5	6	7
Air velocity, m/s	17.8	12	7.9
Spray area, m^2	0.2	.5	1.0
Liter/sqm*min	250	100	50
g water/m^2*min	230	140	106
m^3/s air-water vapour mix	3.6	6	7.9

Table 2. Water content in spray (5)

The system is able, according to Professor Göran Holmstedt, to tackle some fires having a 10 MW heat release rate (HRR). Thus, its effect on smoke cooling is estimated as a volumetric cooling flow rate, from different initial temperatures down to 100°C, which gives:

- 25 m^3/s for smoke at 200°C
- 15 m^3/s for smoke at 300°C
- 12 m^3/s for smoke at 400°C
- 10 m^3/s for smoke at 500°C
- 9.3 m^3/s for smoke at 600°C
- 8.2 m^3/s for smoke at 800°C

Full scale trials were then reported in the document, and there are especially two of them which are of interest. Please keep in mind that we still are 100 bars and 15 litres below the actual working conditions (actually 200 bars and 46 L/min).

- The first was made in Dösjebro (municipality of Kävlinge, Sweden) and consisted of a succession of sprayings stopped when a temperature drop under 200°C was reached. The fuel used was a wooden pallet pile (no more precision) built in the centre of a 11 x 8 m room, giving a volume of 250 m^3. No details were given about the area of openings, but it seems that the fire was air–controlled.
- The second one was done in Oslo (Norway), and attention was paid to keeping a fuel controlled fire. The room volume was approximately 600 m^3 (10 x 13 x 4 m) and the area of the opening was greater than 6 m^2. The protocols followed were the same as in Dösjebro.

The water jet direction was horizontal in each of the trials, but was not targeting the core of the fire, in order to show the ability of volumetric action of the mist produced.
Four spraying were done, per burning, on the first trial:

1. A fixed lance (40 L/min)
2. A fixed lance and a pistol (70 L/min)
3. A Pistol (30 L/min)
4. A fixed lance and a pistol (70 L/min)

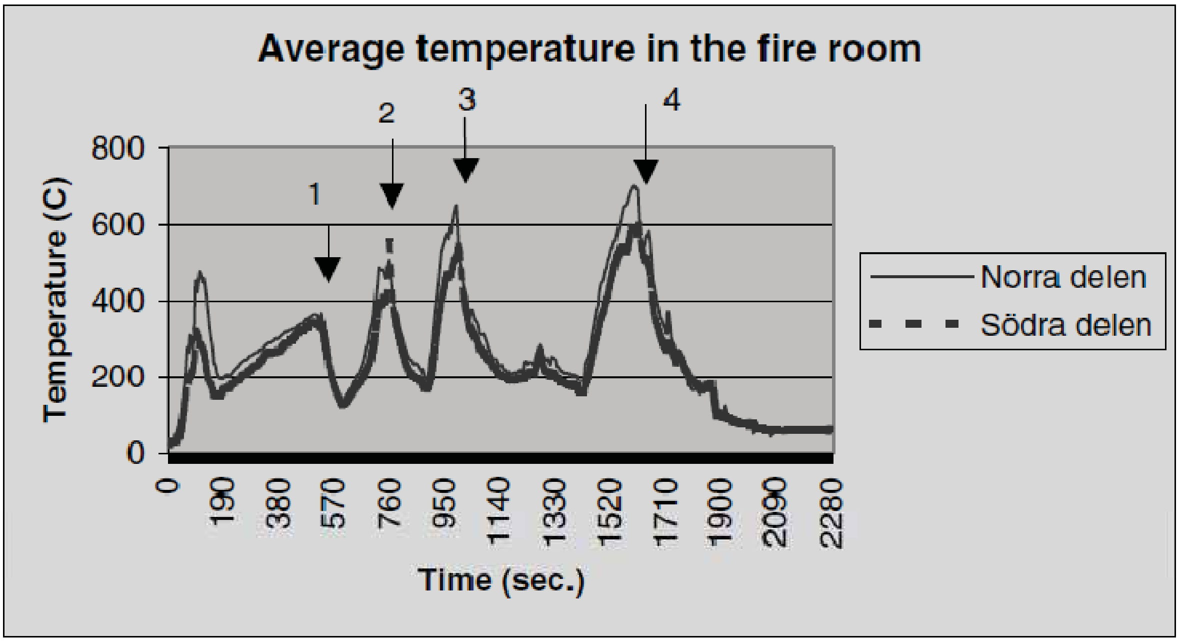


Figure 5, Average temperature in the fire room's northern and southern parts

Figure 5. Temperature evolution, time dependent. (5)

(Temperature evolution, time dependent, in Dösjebro. Each arrow shows the start of a spraying)

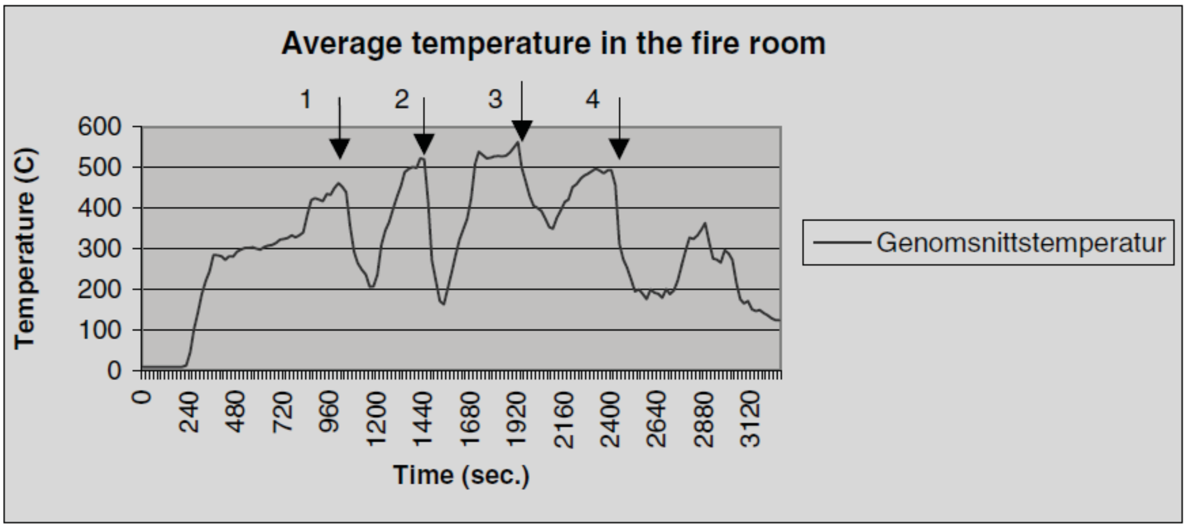


Figure 6, Average temperature in the fire room

Figure 6. Temperature evolution, time dependent, in Oslo (5)

(Temperature evolution, time dependent, in Oslo. Each arrow shows the start of a spraying)

In both cases, the total amount of water used never exceeded 200 litres, and no water was visible on the floor. Assumption made by Göran Holmstedt that all the water was used in the vaporization process seems to be confirmed. However, this will be discussed later in the light of our findings, showed in the results section.

It was concluded from this in-depth study that the Cutting Extinguisher has a very efficient effect on a room up to 150 m^2, and 10-12 MW. Moreover, it reduces the overall temperature, irrespective of where the jet is directed, if the distance of 5 metres before splitting point is respected, in order to produce the desired mist. The maximum distance of efficiency is estimated as being at least 15 m. It is better to have as small openings as possible, in order to increase the inerting effect. However there is still the need for conventional BA team action, after fire knock down by the Cutting Extinguisher, to completely extinguish the remaining charring combustion.

At the same time, the Swedish Defence Materiel Administration (FMV) was interested in the Cutting Extinguisher, to see if it could be a sustainable solution for fire fighting on-board a naval ship environment. They instructed two students from the Lund University of Technology. Unfortunately the main document being in Swedish, it cannot be used as a safe source of information. Thanks to some figures it was however possible to notice that some tests were done, in rooms corresponding to such a design:

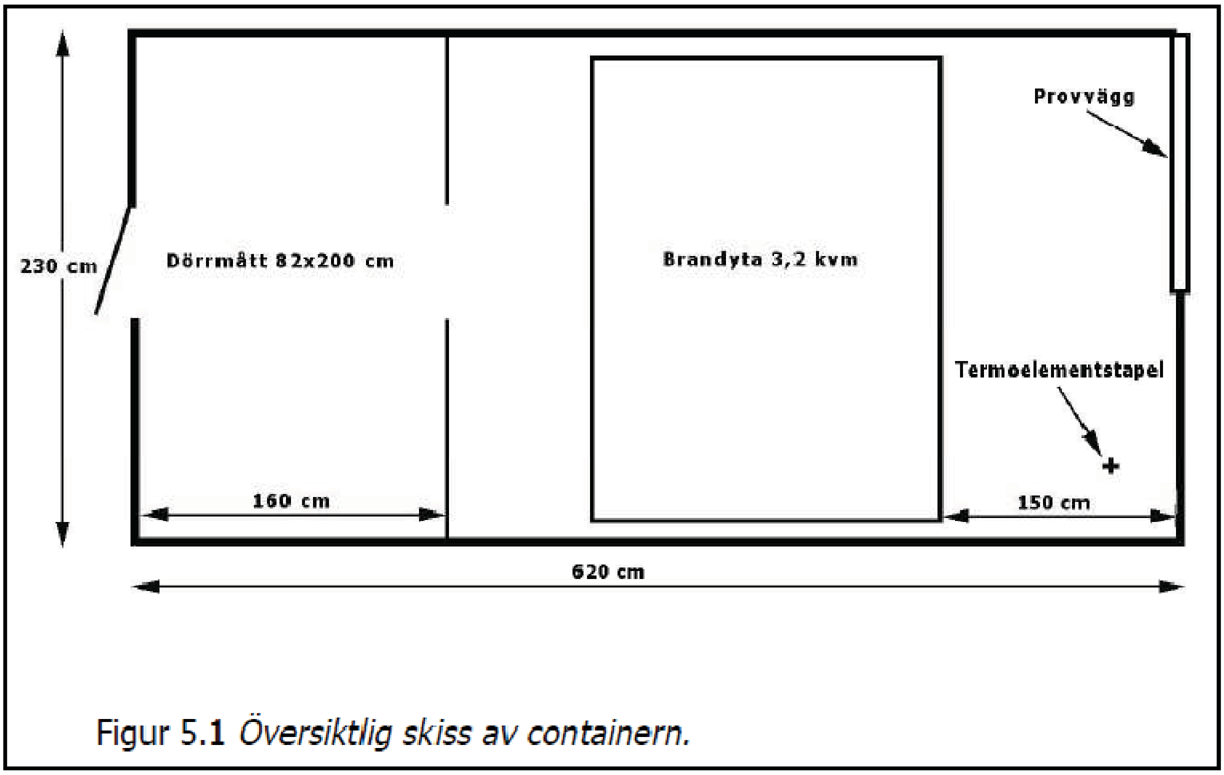


Figure 7. Shape of the compartment (7)

The measured parameter was again temperature, and thermocouples were located at the bottom right corner of the compartment, on a straight column, giving some astonishing temperature drops. They were created by a hydrocarbon pool fire, having an area of 3.2 m^2, and 5 minutes pre-burn, before 30 seconds spraying.

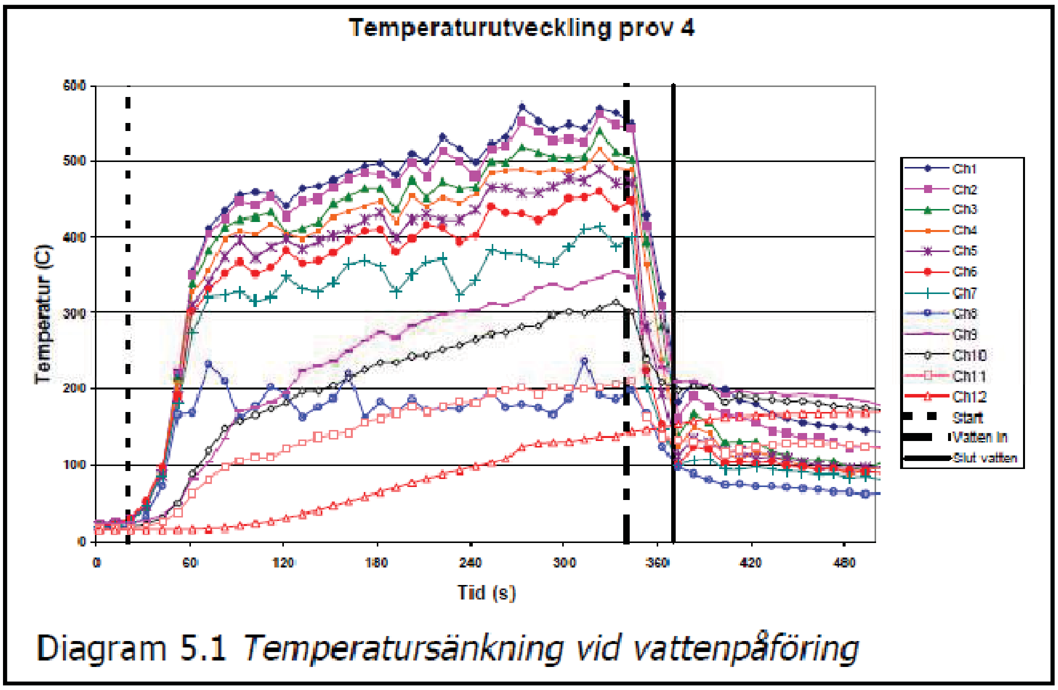


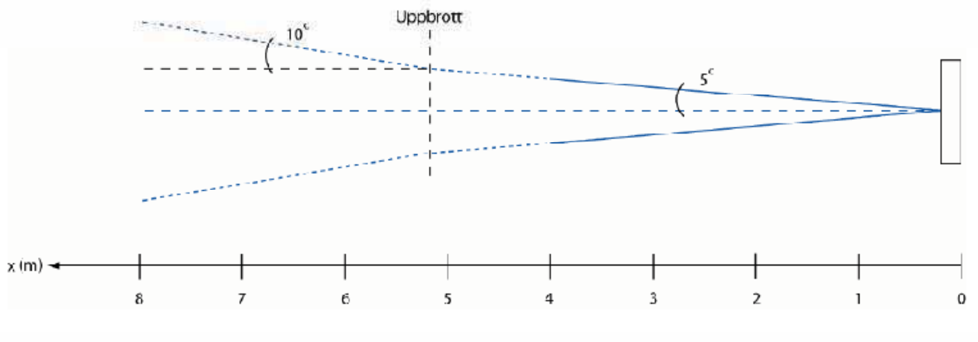
Figure 8. Temperature evolution, time dependant (7)

However, it was possible to get a draft paper in English, summarizing the previous document. It is a "Report on completed tests with Cutting Extinguishers", from the Swedish FMV again, and dated from 07th February 2001. There are few missing pages, but it still enables us to understand the type of study undertaken.
It first explained the issues of a fire outbreak on a naval ship environment, and especially the Swedish Corvettes, class Visby, which are entirely constructed in carbon fibre laminate, as so to defeat radar detection. However, we must know that this sort of material is extremely hard to cut or drill, since it fouls chainsaws, grinders and drillers due to the fibrous and layered composition. It is also impossible to break with a mass, because of its high level of elasticity. And finally, regarding it behaviour when it is subjected to heat, it is important to know that is starts losing its load bearing capacities at approximately 80°C, and releases extremely toxic gases, which could inflict severe injuries on crewmembers (and fire fighters).
The Cutting Extinguisher was tested for its ability to cut holes in a hard range of very hard materials.

- 4 mm steel plates were passed within 10 s
- 8 mm carbon-fibre laminate was passed within 10 s
- 50 mm garden variety concrete plates was passed without noticing resilience.

Regarding the fire tests done, we learn that there were several sessions and type of fires, involving fire extinguishing of 8 painted chipboard in compartment, extinguishing open diesel pool fires of 5 m^2, and extinguishing Liquefied Petroleum Gas (LPG). The type of nozzle used provided a flow rate of 30 L/min for a working pressure of 260 bar.
The conclusions did not outline any relevant details, leaving aside the cooling ability of all the fires, and the need of an addition of foam fluid (3 %) for the diesel open pool fire. The astonishing low water content required was also mentioned, as well as the ability of the mist to have an action regardless to the direction of the jet (targeting the fire or not).
The disadvantages mentioned in the document were mostly due to the naval ship environment that increases constraints of weight, size of the lance, and allows access into most closed space, if it falls into the wrong hands.
Regarding the Cutting Extinguisher itself, it was noted that the method does not make a complete substitution of conventional solutions for fire fighting, and need the addition of film forming foam in certain cases of open space fires.

The two last documents were published in 2007 and 2010, and are still using the same parameters of pressure and flow rate that we did, namely 300 bar and 60 L/min.
The one from 2007 is a report from the Lund University of Technology, in Sweden, by Johannes Bjerregaard and Daniel Olsson (8). Fully written in Swedish language, it seems to focus only on cutting properties and jet characteristics in a cold situation. The abstract mentions the fact that the break up point of the jet appeared at approximately 5 metres from the mouthpiece, producing a cone of mist 10° wide from the mouthpiece, widened to 30° after the splitting point:



Figur 7. Vattenstrålens uppbrott

Figure 9. Conical shape of the jet (7)

Other very useful spray characteristics are calculated and measured experimentally, such as the spray velocity at different distances from the mouthpiece:

- In the centreline of the jet, (17 m/s at 5 m, 15 at 6m, 12.7 at 7 m, and 10.5 at 8 m.)
- And at half distance of the external ring 11.7 m/s at 5 m, 10.1 at 6 m, 8.8 at 7 m, 7.2 at 8 m)

The radius (r) of the mist ring, from 5 up to 8 metres has been estimated as following the equation, with x being the distance from the mouthpiece:

$$r = 0.153 \times x - 0.311$$

That allows estimations of the cross sectional area of the spray, which was verified by experimental measurement.

Mass and volume flow rate of air entrained by the velocity of the droplets, depending on the distance of the mouthpiece was also calculated. It then allowed us to estimate the mass content of water per cubic metre of mist, which reaches 70 g/m^3 at 5 metres and decreases to 40 g/m^3 at 8 metres. Compared to the known requirement of water content in order to extinguish a diffusion flame, which are at least of 140 g/m^3, and represents 200 % of the capabilities of the Cutting Extinguisher in its best configuration (at 5 metres), we can reasonably estimate that the flame cooling by heat extraction is not the major effect in fire extinguishing with this lance.

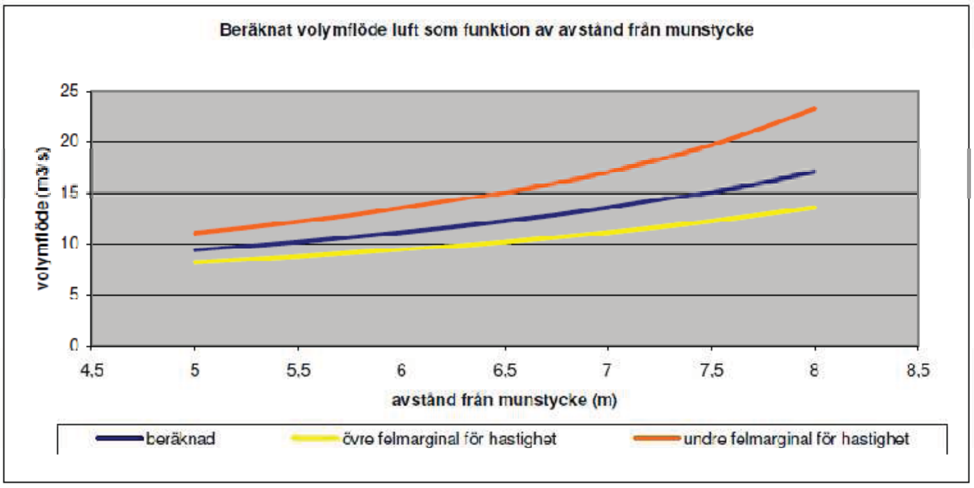


Diagram 9. Beräknat volymflöde luft som funktion av avstånd från munstycket

Figure 10. Generated mist volume in function of distance from mouthpiece (7)

However, keeping focused on the cooling effect on the gaseous phase, and especially the hot smoke gases, Daniel Olsson and Johannes Bjerregaard calculated the maximal gas volume cooling capacity below the 200 and 100 °C limit per second. Transformed into values depending on time, for a constant amount of 100 m^3 of smoke, the graph of time decay graph in function of temperature is quite representative. The red line shows values for an initial gas temperature of 600 °C, whereas the blue one starts at 800 °C.

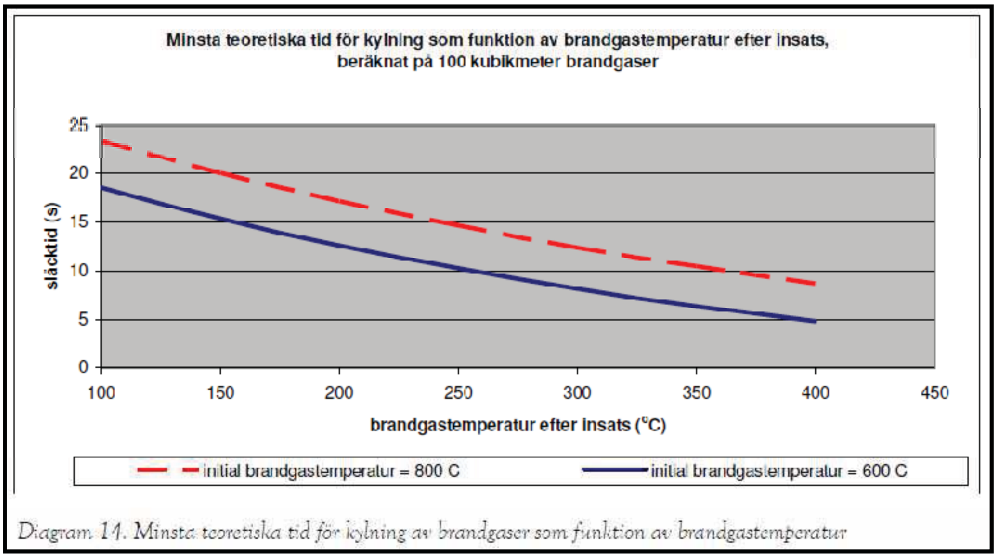


Figure 11. Cooling time in function of smoke temperature (7)

The last document, and the most up to date (Spring 2010) is a "draft for discussion at FIREFIGHT II Madrid meeting". It has been commissioned by the Swedish Rescue Services Agency (SRSA), now the Swedish Civil Contingencies Agency (MSB), and is called "Cutting Extinguishing Concept – practical and operational use -" (9). It contains a summary of all the tests done with the Cutting extinguisher up to now, and contains a part regarding the mist characteristics and properties, and the experiments in real fire situation, but these parts are unfortunately not translated yet, and are only available in Swedish. Despite the language barrier, we still get some illumination on the properties of the small droplets, and typically on the disadvantage of the small size surface wetting, since they tend to "bounce" off a hot surface instead of spreading over the charring material, due to a too small number of Webber (We).
Moreover, some crucial questions are asked in the document, highlighting some lack of knowledge concerning the Cutting Extinguisher:
"How this scenario with a focused jet of water and high flow rate, where the beam is broken up into small droplets, affects the mixing of the fire gases has not so far as known been investigated"
Other questions and mysteries remain as to the density of the water mist after the break up point, in function of the distance from the theoretical direction.

In addition, this document wanting to be a report of acquired information from the first prototype and after ten years of use, suggest some avenues of further research and development, and wishing to develop further the so called CEC. Four main points are mentioned, and quoted below (9):

- *"the droplet size distribution in the use of the cutting extinguisher and the effect of possible variations of the pressure on the size of the droplets - This information is not available at* *present but is important to determine for explaining when and how the cutting extinguisher works*

- *the impact of the ventilation openings on the cutting extinguishers ability to extinguish fires - the ventilation is one of the most important parameters for fire fighting and what importance ventilation has when the cutting extinguisher is used could be examined in experiments and by more systematic theoretical studies*
- *the functioning of the cutting extinguisher in a well controlled fire in relation to various types of and ventilation - how sensitive is the cutting extinguisher when inerting in respect to the type of fuel, geometry and its positioning and the aiming of the beam in relation to the fuel*
- *the importance for the efficiency of the cutting extinguisher of the water jet being able to break up - explanations of the experiences of tests that show that cutting extinguisher can mitigate fire, for instance fires in ceilings when the beam cannot break up and the injection of water only lasts a few seconds or if the beam hits an object on the way to the fire or the water is injected at a considerable distance from the fire"*

At the start this was only a single tool, but now it is integrated into a whole new concept of fire fighting, the Cutting Extinguisher in now at the centre of the European project FIREFIGHT II "The New Age of Fire fighting", and extensively used around the world. However, some of the mechanisms providing such a dynamic water jet those extinguishment capabilities are still not fully understood. That is why, starting from this statement, we chose the following dissertation topic, which is: "An Assessment of the Fire Suppression Capabilities of Water Mist". The aim of this study is to answer partly or fully to some of the remaining questions, but also to generate new knowledge concerning the effects of the water mist produced by the Cutting Extinguisher, and in this way, improve the tactics employed in its use, and exploit all its potential. This study may also provide an occasion to define some limitation of working, depending on the fuel load, the ventilation factor, or its use in degraded mode (only one pump running), or outline some hidden effect on the involved structure and on the victims potentially present.

Aims and objectives

More than assessing the fire suppression capabilities of the water mist produced by the cutting extinguisher, which has already been proven, and is now stated in the literature, we propose to study in depth the influence of three parameters. One of them is often mentioned, and generates the perpetual question of the difference of efficiency on fire in enclosed space, or partially open, or fully open, producing either ventilation or fuel controlled fires.
We will then focus on the influence of the area of the openings.

The second issue concerns the fuel load. It is stated in the literature that the fires are harder to extinguish when they result from combustion of solid fuel, rather than from a liquid or gaseous combustible. This can be sustained by the fact that the small droplets of the water mist have a poor effect on surface shielding.
Therefore, we will focus on the influence on the surface of burning solid fuel.

The third question was generated after the assessment of Johannes Bjerregaard and Daniel Olsson (Skärsläkaren – experimentella försök och beräkningar, 2007 (8)), where it is explained that the water content in a volume of air is two times too low to be sufficient to extinguish a diffusion flame, which lead us to suppose that the ability of fire extinguishing of the Cutting Extinguisher was mainly dominated by oxygen depletion. Dividing the initial flow rate by two would then once more increase the difficulty to tackle a flame.

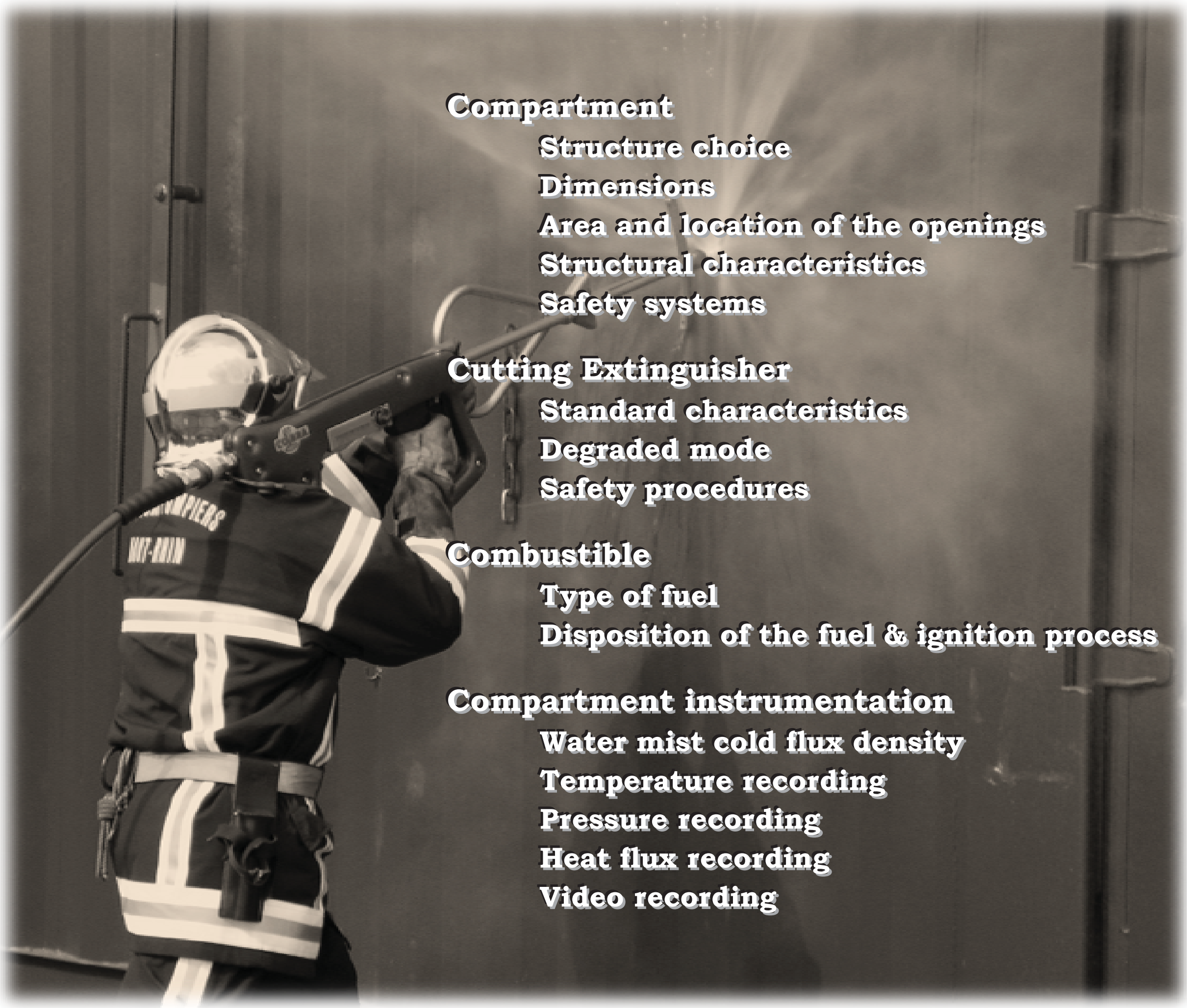
That is why we will study the influence of the flow rate.

In a second section, it is important in our sense, to study the characteristics of the jet, and the spray pattern. Even if it has already been studied in some previous research, we will show the behaviour of the jet, and then the mist, and establish the assumption that the air streams generated by the jet velocity predominate on the pattern established by the fire development. This will allow us to answer the question asked in the "Cutting Extinguishing Concept – practical and operational use -" by the Swedish Civil Contingencies Agency (MSB). In order to remain credible, we will confirm our hypothesis thanks to a volumetric real time scanning of the temperatures in the compartment; assuming that the temperature drops assesses the presence of mist on its location.

Finally, we will also pay attention to the case of a potential victim, or fire fighters in the fire room, and possible damage to the structure when the Cutting Extinguisher is used, which could modify the heat flux exposure, the visibility and presence of a cold layer at the floor, and cause windows to break due to pressure effect.

The questions of the influence of the mist on radiation, on gas mixing, expansion or contraction, and steam generation will then be kept in mind as well.

Experimental Framework



Experimental framework

Compartment

Structure choice

The chosen compartment is actually a Compartment Fire Behaviour Training structure (CFBT) from the Fire fighting School of Colmar, in France. (Ecole Des Sapeurs Pompiers du Haut-Rhin, SDIS 68, France).

It has been decided to make the choice of this location for several reasons, and furthermore the inherent characteristics of the enclosure meet the demands of the experiment:

- For the need of a lance: Since the studied water mist nozzle is the Cutting Extinguisher, we required a system, and it appeared that the French Company selling the Cutting Extinguisher were not using its presentation vehicle during the period of the experiments.
- For convenience: Some fire fighters were already aware of the uses of the Cutting Extinguisher, in the area of Colmar, and would then be a precious help for logistic issues, and labour for preparing the burnings, ensuring safety, rehabilitating and storing the equipment afterwards.
- For the interest of the Fire Brigade: the Fire Services has started to study the CEC for a use by the Haut-Rhin fire fighters, and was then glad to take this opportunity to step into the experimental program, and get the results of the data analysis. They then offered to loan their training compartment.
- For cost reasons: The compartment hire is free, which was an essential parameter, since it is important to reduce to the minimum the costs of the research.

Figure 12. The enclosure housing the experiments. Picture: Service communication SDIS68

Dimensions

The enclosure is a standard 40 feet compartment. The width and height dimensions are 8 feet. In metres the internal dimensions are: 12.20 x 2.40x 2.40 m

The real part of the compartment involved by the fire is 1.50 m shorter and is 10.70 m long, but has the same height and width. From now we will name it “Compartment”. We can then estimate the volume of the compartment:

$$V_e = 2{,}44 \times 2{,}44 \times 10{,}70 = 63{,}70$$
$$V_e = [m] \times [m] \times [m] = [m^3]$$

Area and location of the openings

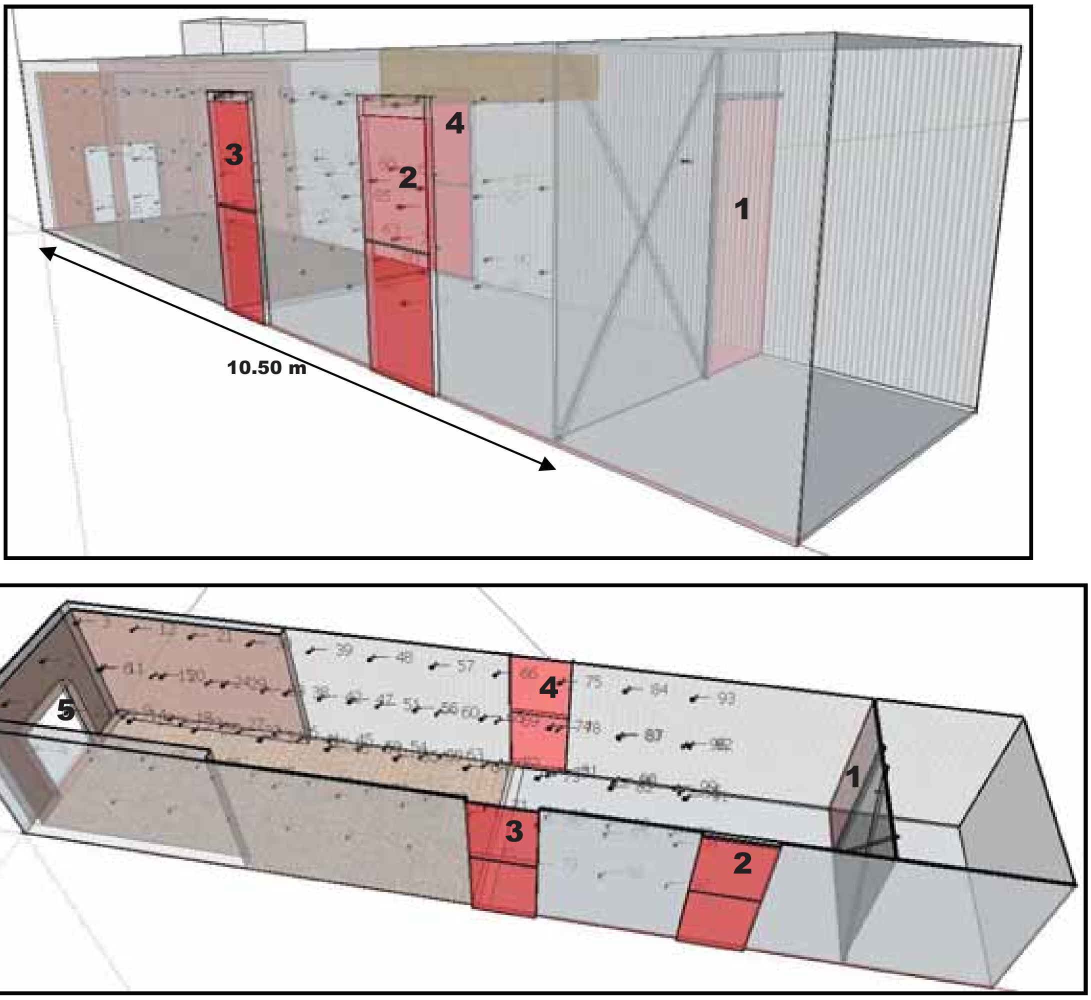


Figure 13. Location of the openings

The compartment has six possible openings:

- The main entrance (opening 1) has 2.10 m height and 0.8 m width
- The three lateral doors (openings 2, 3 and 4) are barn/stable doors. They have following dimensions: (2 x 1.05) x 0.8.
- The trap waste disposal (opening 5) has 1.20 m height and 1 m width.
- The safety vent on the ceiling (greyish chimney on the first figure) has a 1m² surface.

When all the openings are closed, we could consider the compartment as being sealed. However, the gaps under and above the panes are estimated at 1 cm on all the length of the opening, except under the door 1 where the gap is 5 cm; giving a total leakage area of:

$$A_c = (0.01 \times 1) \times 4 + (0.01 \times 0.8) \times 10 + (0.01 \times 1.6) \times 2 + (0.05 \times 0.8) = 0.192$$
$$A_o = [m] \times [m] \times [no\ unit] = [m^2]$$

We can consider that the scenarios with the compartment having some openings will have the opening 2 completely open (representing a forgotten open door) and the upper pane of the opening 4 (representing a broken window), which gives us a maximum total area of the openings of:

$$A_o = 1.05 \times 0{,}8 \times 3 + A_c = 2.71$$

Structural characteristics

Considering the characteristics having a possible influence on the experiments, we should note the presence of a 1 m² smoke vent, 3.85 m from the bottom of the compartment, which can be pulled open both from inside and outside. It will be used according to the will of the burning operator, in order to regulate combustion and remove moisture.
It is also equipped with two smoke curtains, one mobile, located at 3.20 m from the bottom, and being 0.60 m high, and another having the same length and being at 8.50 from the bottom.
All the compartment boundaries are steel sheets, being 4 mm thick, and the fire zone (in brown on the figure above) is 3 m long from the bottom, and is doubled by CorTen steel with a clearance in between of 100-150 mm.
Finally, we must also take into account the internal lining of the "burning area" (in brown), which is covered by refractory bricks, on all the width and height, on a length of 6 m.

Safety systems

In case of overpressure, in order to preserve the compartment, the smoke vent will be used as a safety system. It is openable from outside, and is only closed by its self weight, which then allows it to open under the push of pressure.

Cutting Extinguisher

The Cutting Extinguisher used for the experiments is installed in a demo vehicle, and owned by the French Company Fire Technologies.

Standard characteristics

The standard characteristics of the Cutting Extinguisher we used for our experiments are the same as most of the units, except for some very specific ones. It has two high pressure pumps with a flow rate of 28 litres per minute each. They are powered by petrol engines. Its working pressure is therefore 300 bars at the pump, for a total exact flow rate of 56 L/min (0.93 L/s), through a mouthpiece of 2.3 mm of diameter. The nozzle is actually a hand-held lance combined with a radio transmitter to the pump starter. The 80 metres hose is mounted on a hose-reel; the water velocity in it is exactly 4 m/s, generating a pressure loss of 40 bars per 100 metres. The abrasive is stored in a 10 litres pressure vessel, and water is taken from an independent water reservoir. The figure below illustrates networking principle on an exploded diagram.

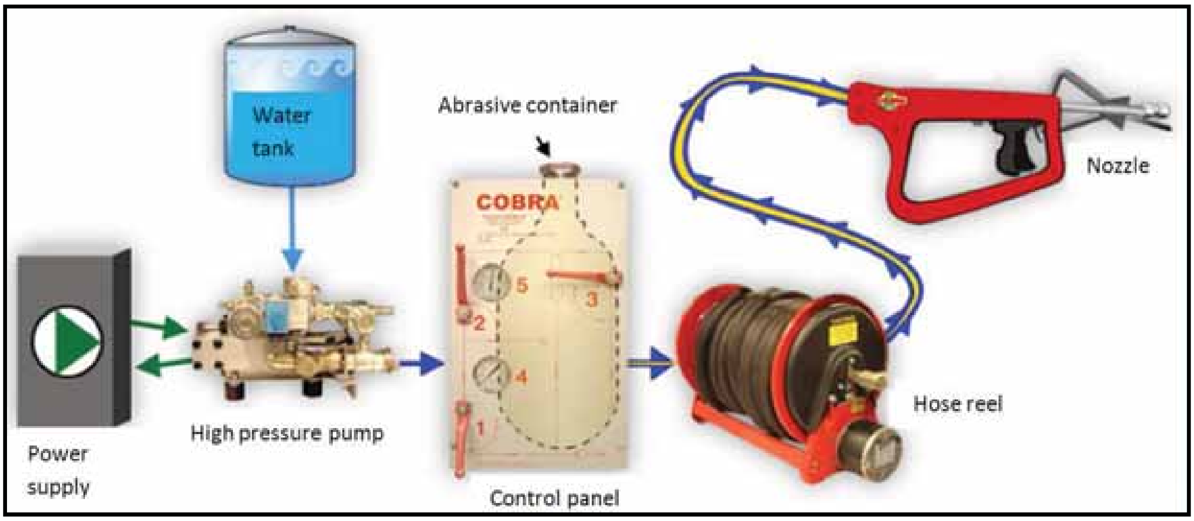


Figure 14. Exploded diagram of the major elements of the Cutting Extinguisher used for the experiments

From these parameters, we could determine the velocity of the flow coming out of the mouthpiece (V_m). For this, we use Bernoulli's equation, which is:

$$V_m = \sqrt{\frac{2P_m}{\rho} + {V_h}^2}$$

With:

- V_m = Velocity at the mouthpiece
- P_m = Pressure at the mouthpiece
- V_h = Velocity in the hose(4 m/s)
- ρ = Water density (1000 kg/m^3(

Since the nozzle is 80 metres f from the pump, the pressure at the mouthpiece is:

$$P_m = P_p - l_h \times \frac{P_l}{100} = 300 - 80 \times \frac{40}{100} = 268\ bars$$

With:

- P_p = Pressure at the pump
- l_h = length of the hose (80 m)
- P_l = Pressure loss (40 bars/100 m)

We can now deduce the flow velocity at the mouthpiece, using the simplified equation without ${V_h}^2$ as it is negligible in comparison to V_m:

$$V_m \approx \sqrt{\frac{2P_m}{\rho}} = \sqrt{\frac{2 \times 268 \times 101325}{1000}} = 233\ m/s$$

Second step of our calculations, we can find the coefficient of flow arising from contraction (C) which is:

$$Q = C \times A \times V_m \leftrightarrow C = \frac{Q}{A \times V_m} = \frac{9.33 \times 10^{-4}}{4.15 \times 10^{-6} \times 233} = 0.964$$

With:
- Q = Flow rate (56 L/min or $9.33 \times 10^{-4}\ m^3/s$)
- A = cross sectional area of the mouthpiece orifice ($4.15 \times 10^{-6}\ m^2$)

$$A = \left(\frac{D}{2}\right)^2 \times \pi = \left(\frac{0.0023}{2}\right)^2 \times \pi = 4.15 \times 10^{-6}\ m^2$$

Third step, we can now estimate the reaction force from the nozzle, using Newton's second law:

$$R = C \times A \times P_m \times 2 = 0.964 \times 4.15 \times 10^{-6} \times 268 \times 101325 \times 2 = 218\ N$$

Which gives, in kg, a value of 22 kg ($\frac{218}{9.81} = 22.18\ kg$) reaction weight.

Degraded mode

As the Cutting Extinguisher is supplied by two high pressure pumps, themselves powered by two petrol engines, there is a possibility of working on a so called "degraded mode". This mode is used in the case of one engine is not working anymore; and there is a need to change the nozzle from 2.3 mm orifice diameter to a 1.6 mm one. The flow rate is decreased to 28 L/min, but pressure is then sustained at 300 bars, giving the same velocity at the mouthpiece.
The coefficient of flow however, is changed to:

$$Q_d = C_d \times A_d \times V_m \leftrightarrow C_d = \frac{Q_d}{A_d \times V_m} = \frac{4.67 \times 10^{-4}}{2.01 \times 10^{-6} \times 233} = 0.996$$

With:
- Q_d = Degraded mode flow rate (28 L/min or $4.67 \times 10^{-4}\ m^3/s$)
- A_d = Degraded mode cross sectional area of the mouthpiece orifice ($2.01 \times 10^{-6}\ m^2$)

$$A_d = \left(\frac{D_d}{2}\right)^2 \times \pi = \left(\frac{0.0016}{2}\right)^2 \times \pi = 2.01 \times 10^{-6}\ m^2$$

This also influences the calculations of the Reaction force, which in this case is:

$$R_d = C_d \times A_d \times P_m \times 2 = 0.996 \times 2.01 \times 10^{-6} \times 268 \times 101325 \times 2 = 109\ N$$

Which gives, in kg, a value of 11 kg ($\frac{109}{9.81} = 11.09\ kg$) reaction weight.

Safety procedures

In order to carry out the experiments in a safe manner, some safety procedures have been followed, inspired by the recommendations of use given to the fire fighters. They are listed below:

- The nozzle user is the only one who has the radio transmitter. He always has to separate it from the lance when it is not in use
- When the Cutting Extinguisher is operating, nobody should be in the 5 metres restricted area for fire fighters and 10 metres for civilians
- During foreground movement, the mouth piece should always be directed to the floor (as when carrying a rifle)
- Always wear breathing apparatus as well as the entire fire fighting personal protective equipment (PPE)

Combustible

Type of fuel

The fuel used was standard 18 mm chipboard. The standard fuel load in the compartment was composed of five panels: two on the ceiling, having dimensions of 150 x 200 cm, with an overlap of 50 cm; one on each side wall, having dimensions of 120 x 250 cm; and one on the bottom wall having dimensions of 120 x 200. The disposition was made as shown below:

Figure 15. Fuel arrangement

Disposition of the fuel & ignition process

Since the compartment is square, and has special made hooks, we arranged the panel as shown in the picture above.

Regarding the combustible area, in the case of full combustion (all the boards), the surface of the panels is:

$$S_f = [(1.5 \times 2) - 0.5] \times 2 + (1.2 \times 2.5) \times 2 + (1.2 \times 2) = 12.8$$
$$S_f = [m] \times [m] = [m^2]$$

And where the scenario involved fuel reduction, one of the ceiling board, and the left board were removed (suppressing boards number 2 and 4), giving the reduced area of:

$$S_r = (1.5 \times 2) + (1.2 \times 2.5) + (1.2 \times 2) = 8.4$$

The reduction ratio between the two possible scenarios is then:

$$R_r = \frac{S_r}{S_f} = \frac{8.4}{12.8} = 0.656 = 65.6\ \%$$

The ignition is made on cribs and expanded plastic material at the bottom right hand corner (also visible on the picture). A torch was used to ignite them.

Compartment instrumentation

As mentioned in the aims and objectives, we proposed to study the influence of different openings, different fuel surfaces, and different water mist flow rates. Attention should also be paid to the characteristics of the jet, and the spray pattern. And finally, we also suggested seizing the opportunity of the experiments to try to answer the questions of the influence of the mist on radiation, on gas mixing, expansion or contraction, and steam generation. To give us the means to do this, we proceeded step by step. The compartment being completely new, we took the opportunity to establish the water mist flux density pattern first, for convenience reasons.

Water mist cold flux density

Starting from an observation of the Cutting Extinguisher jet in a free area, and the work done by Bjeregaard and Olsson (2007), we supposed that the water mist was mainly following the direction given by the jet, before the break up point.

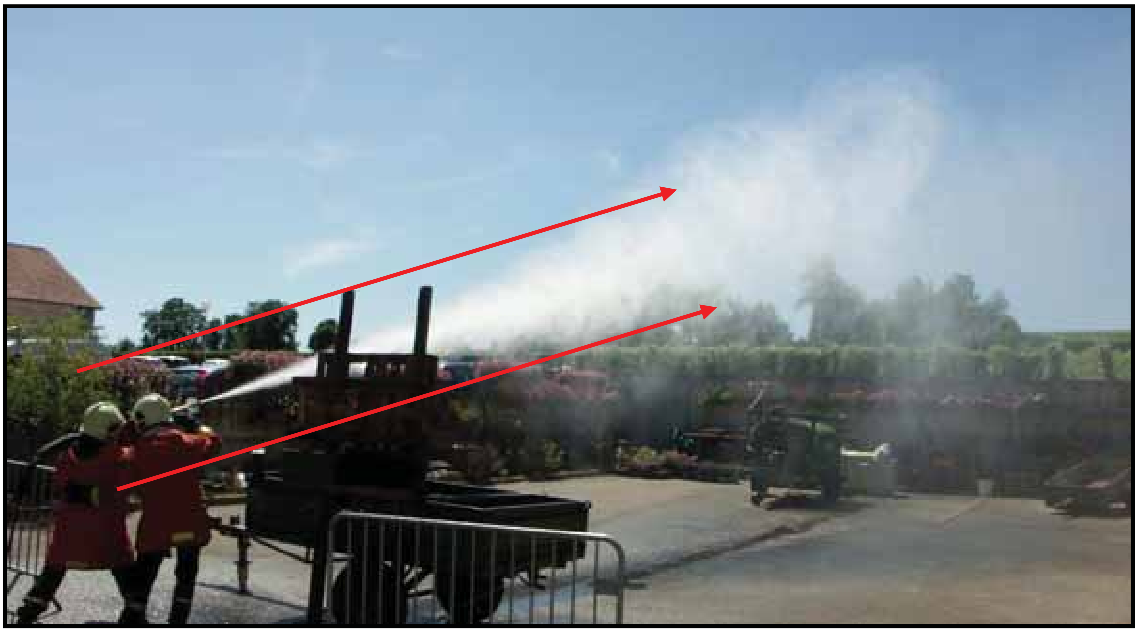


Figure 16. Mist displacement, following the direction given by the jet

We then imagined a way of measuring the amount of water distributed within a determined spraying time, assuming the main part of the water mist cloud is moving forward, compared with the jet direction. The idea would be to establish a figure showing the repartition of water within the spray, thanks to cross sectional plans of the jet at several distances. Spraying towards a wall without gaps is not a good solution, since it deflects the fog, without collecting the real quantities of water per cross sectional area, we thought on building a so called “bottle frame”.

This “bottle frame” consists of dividing the cross section of the compartment in a meshing of small square surfaces of the same size. Each square has in its centre (at the intersection of its diagonals) a cylindrical bottle, which can rotate on the horizontal axis, so that when it fills with water, it will tend to rotate and keep its contents. All the bottles have the same weight, are cut in the same shape, and have the same internal diameter. The external frame was made of wood beams, having 7 cm cross section. They were secured with the help of wooden wedges, firmly secured to the wall of the compartment. The bottles were pierced from side to side by a steel wire allowing them displacement on the horizontal axis, and maintained on the vertical axis by another wire blocking their movement.

The picture below illustrates the “bottle frame” device, during its construction:

Figure 17. “Bottle frame” construction, inside the compartment

The “bottle frame” was 2.38 m width over 2.38 m height, which was calculated to fit as precisely as possible in the compartment, which has 2.40 m width and height. We also changed it into a smaller one, fitting within the burning zone, which is narrower. Due to the wall-hooks for fixing the wooden fire panels, we could not be as precise as in the main part of the compartment; the “bottle frame” was then reduced to 1.80 m width over 2.00 m height

Figure 18. Narrower “bottle frame”

Regardless of the size of the frame, we decided to mesh the cross section into squares 18 x 18 cm, which gives a control surface (A_c) of 324 cm^2.
Supposing the bottles orientate on a parallel with the jet direction, we can estimate the area covered by the bottle (A_b), which are all having a diameter of 8.5 cm:

$$A_b = \left(\frac{D}{2}\right)^2 \times \pi = 56.7\ cm^2$$

This gives us a ratio (R_s) of: $R_s = \frac{A_c}{A_b} = \frac{324}{56.7} = 5.71$.

We know that the bottles are stopping the water mist stream (because of a sealed bottom), and thus deflect a part of the mist, which is a limitation. Furthermore, as they get heavier, it is harder to lift them to a pseudo-horizontal position, which as a consequence will reduce the area of water catching, since the cylinder becomes elliptic, viewed on a cross sectional plan.

However, it has been observed that even the bottles which were empty had difficulties lifting, especially if they were not subjected to the core of the jet, which then will falsify the ratio from the control square to the bottle surface. But if we exclude the false values from the bottles struck by the core of the jet (which may only concern one bottle), we still preserve the ratio from one control square to another on all the rest of the cross section, which is already a useful basis of comparison.

Figure 19. The "bottle frame" in the non fire part of the compartment

The green meshing corresponds to the control surfaces, with one bottle in each centre. Please note that the central beam has been removed, since it was falsifying the values of the row just below, due do water deflection.

Temperature recording

In order to give us the means to achieve the fixed goals, and go even further in data collection, we decided to give greatest importance to the temperature recording. Temperature is the major parameter, which could show the smoke, and later the water mist displacement around the enclosure. Since we want to be capable of understanding the behaviour of fluids on the whole compartment, as well as many other parameters (like representing the fire growth, the smoke layer buoyancy, the temperature at potential height of a fire fighter's head when he is progressing kneeled, the temperature at the floor where a victim would likely lie, etc.), we imagined a solution of real time and continuous temperature scanning and recording. This should cover the entire compartment, and can be achieved by arranging a volumetric meshing of thermocouples. Thanks to the kindness and the dedicated contribution of the Efectis Grouping, which is a fire resistance testing laboratory, we could use a hundred thermocouples. The best way of dividing the 100 inputs, was to use 99 of them, giving a control volume having dimensions of 0.8 m per side. This gave 11 vertical slides of 9 TC; from 0.40 m of the bottom, up to

8.40; from 0.4 m of the floor up to 2.00 and from 0.40 m of the left wall up to 2.00 (and reversible with right wall). The TC were numbered from 1 to 99, slices per slices, on lines, from top left corner to bottom right corner. The **Appendice A1** shows some compartment views with the numbering.

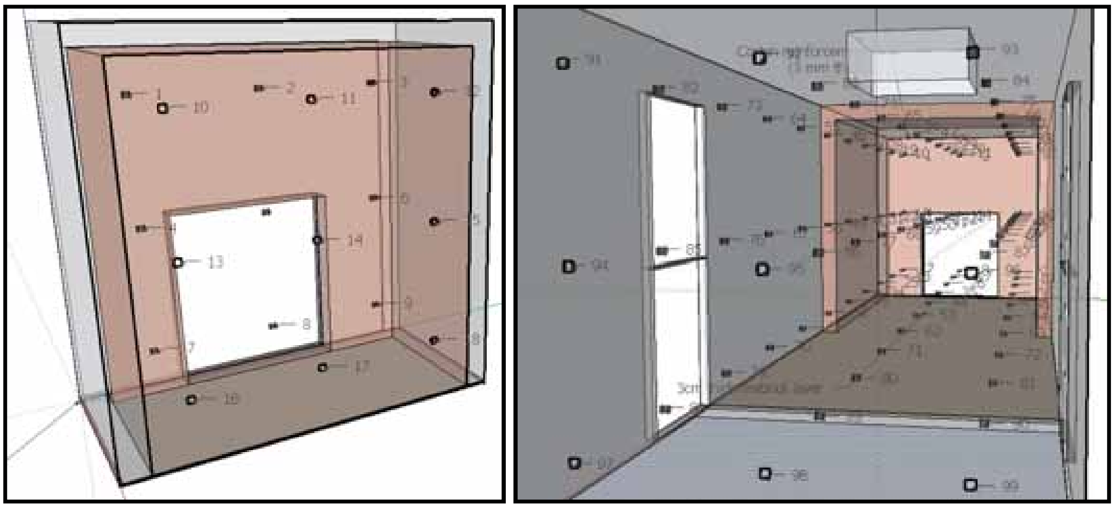


Figure 20. Schematic ideal representation of the thermocouple meshing; left, the two first slides, and right, the entire device.

This sort of meshing allows us to create several cross sectional views:

- Either cutting the compartment in the width and height, giving a plan covered by 9 thermocouples, on 11 slides
- Or in the length and width, giving a plan covered by 33 thermocouples, on 3 slides, at 0.4, 1.20 and 2.00 m height
- Or in the length and height, giving a plan covered by 33 thermocouples, on 3 slides, on the first, second and last third of the compartment.

The support of the meshing was done by creating a steel frame suspended from the ceiling. The frame was made of 20 mm square profile steel beams, based on hooks. On each thermocouple position, a stainless steel wire was running down, and moored to the ground with ballasts. The thermocouples entered the compartment through the gaps under the doors, before climbing along the wires.

Figure 21. Thermocouples meshing

The thermocouples were connected to extension cords, and then running to a data logger, also borrowed by Efectis Group. The data logger works on a process of scanning a single input one after another, with a scanning delay of 50 µs per input. The required time to cover the entire range of TC is then 5 s, which means that we have a temperature recording every 5 seconds on each specified TC.

Figure 22. TC network, running from the compartment to the data logger. Picture: Service communication SDIS68

Pressure recording

When a fire is developing in a sealed compartment, the temperature increase will inevitably raise the pressure, which is demonstrated with the perfect gas law relationship. If the volume is not firmly sealed, the gaps will allow smoke leaking, which will release pressure, and prevent the raise. Since our compartment is quite unsealed, even in the condition of all doors being closed, we might not have significant pressure rise, regardless of the location of the measurement. But extinguishing this fire with water, involves the explained change of state of water, from liquid to vapour, which induces a change of volume occupied by this water. If it does not cool the hot gases, but turns to steam after having struck a wall, the volume increase will generate a pressure increase. If on the other hand, most of the water is vaporized in the gas layer, it is more likely to get a volume reduction, causing a pressure drop (under pressure). It is possible to estimate the minimum percentage that has to vaporize in the hot layer, in order to remain at static pressure, which will be developed in the analysis part. We then proposed to record the pressure variations in the compartment. The expected variations that may be produced by the Cutting Extinguisher are a visible depressurisation, instantly after the jet penetrates the compartment, before a progressive pressure recovery to the state attained before the extinguishing, and maybe a later small pressure generation, when all the gases are cooled, but the boundaries remain hot, which generates steam.

Using a pressure transducer scanning over the range of $\pm 200\ Pa$, which was provided with the TC, we linked it to the data logger. But since the scanning delay between two measurement is 5 s, which was estimated as being too long to be significant, we installed after a while, another pressure transducer scanning every single second. That was only able to recognise pressure over a positive pressure range up to + 500 Pa. Feeling that the use of water mist for fire extinguishing is more likely to generate under-pressure, the piping network was assembled in reverse, measuring only the negative variations.

Due to wide gaps around the doors and frames, and in order not to drill and damage the compartment, we located the pressure canes at 1.05 m and at 2.10 m from the floor and at 6.00 m from the bottom wall.

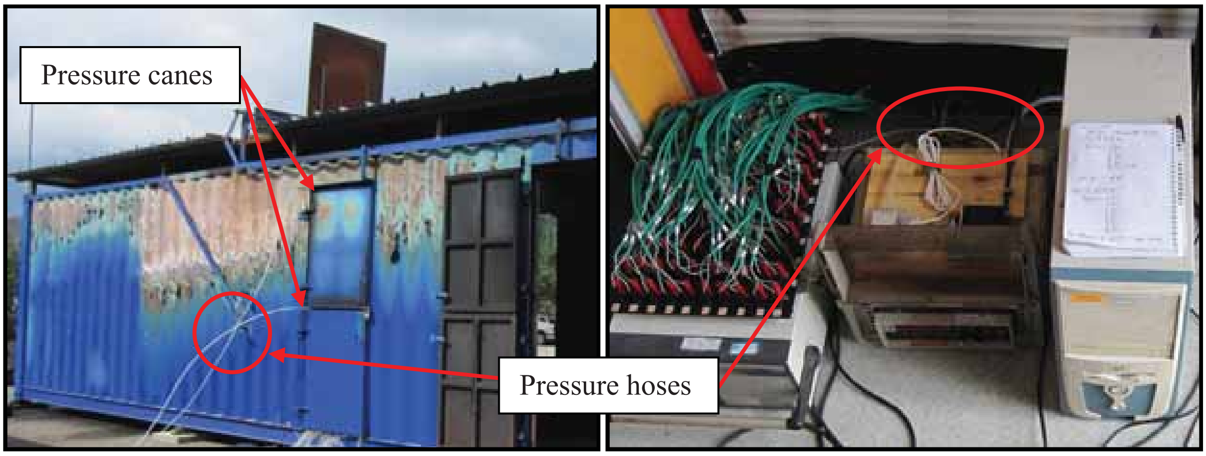


Figure 23. Pressure canes and hoses, in white, from the compartment to the transducers

Heat flux recording

Since one of the five mentioned extinguishing actions of water is radiation attenuation, we took the opportunity to insert a Gardon Gauge Radiometer, measuring heat transfer by radiation and convection. The radiometer, having a short insulated wire length, has been located 7.00 m from the end of the compartment, 0.40 m high, and 0.40 m from left wall (in order to avoid influence of the boundaries). The sensitive plate was targeting the bottom right corner, which is the exact position of the ignition harness.

More than just getting information during fire extinguishing, the interest of adding a radiometer is also to measure the flux that is radiated on a fire fighter. The compartment being a training device for fire behaviour observation, the trainer is kneeling at the exact position where the radiometer was located. The data is then of interest for our study, since we could also consider the presence of a victim lying, but also for the health and safety department of the Haut-Rhin Fire Service, regarding the study of the working conditions of the fire fighters.

The Gardon Gauge radiometer was water cooled, to prevent overheating, and transmitted a tension, in mV to a 1 s speed scanning data logger, independently from the temperature and pressure logger. Its last calibration was in January 2010, we based our calculation on this ratio, which is: 18.32 (the initial calibration, done in 2001 was given a ratio of 20.41). This means that a 1 mV input value corresponds to a heat flux of 18.32 kW/m^2. This relatively low figure allows us for simplicity to neglect the part of heat transfer by convection, and only consider the radiation.

Figure 24. Position of the radiometer in the compartment

Video recording

Whilst not as important as the other instruments, we still decided to make video recording of the burning and extinguishing phases. However, since the cameras needed to be of a minimum heat resistance, we were depended on the presence of some staff from the Fire Service. That is why we cannot establish any comparison, since only a few burnings were recorded. The position of the camera is shown on the figure below:

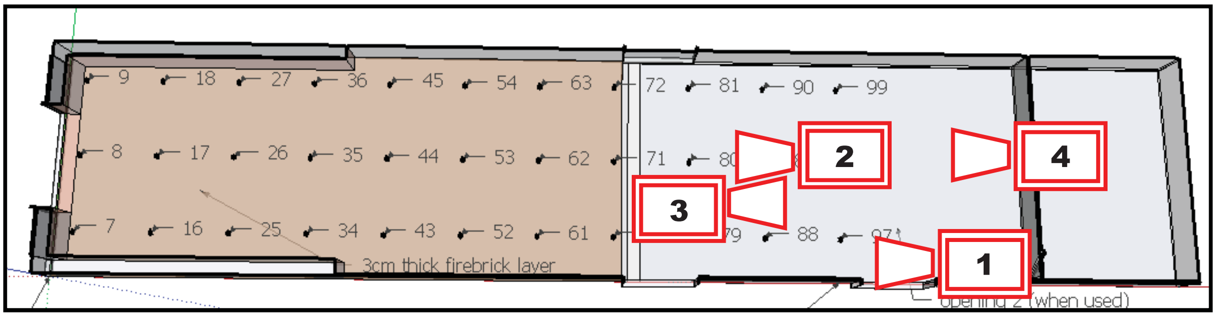


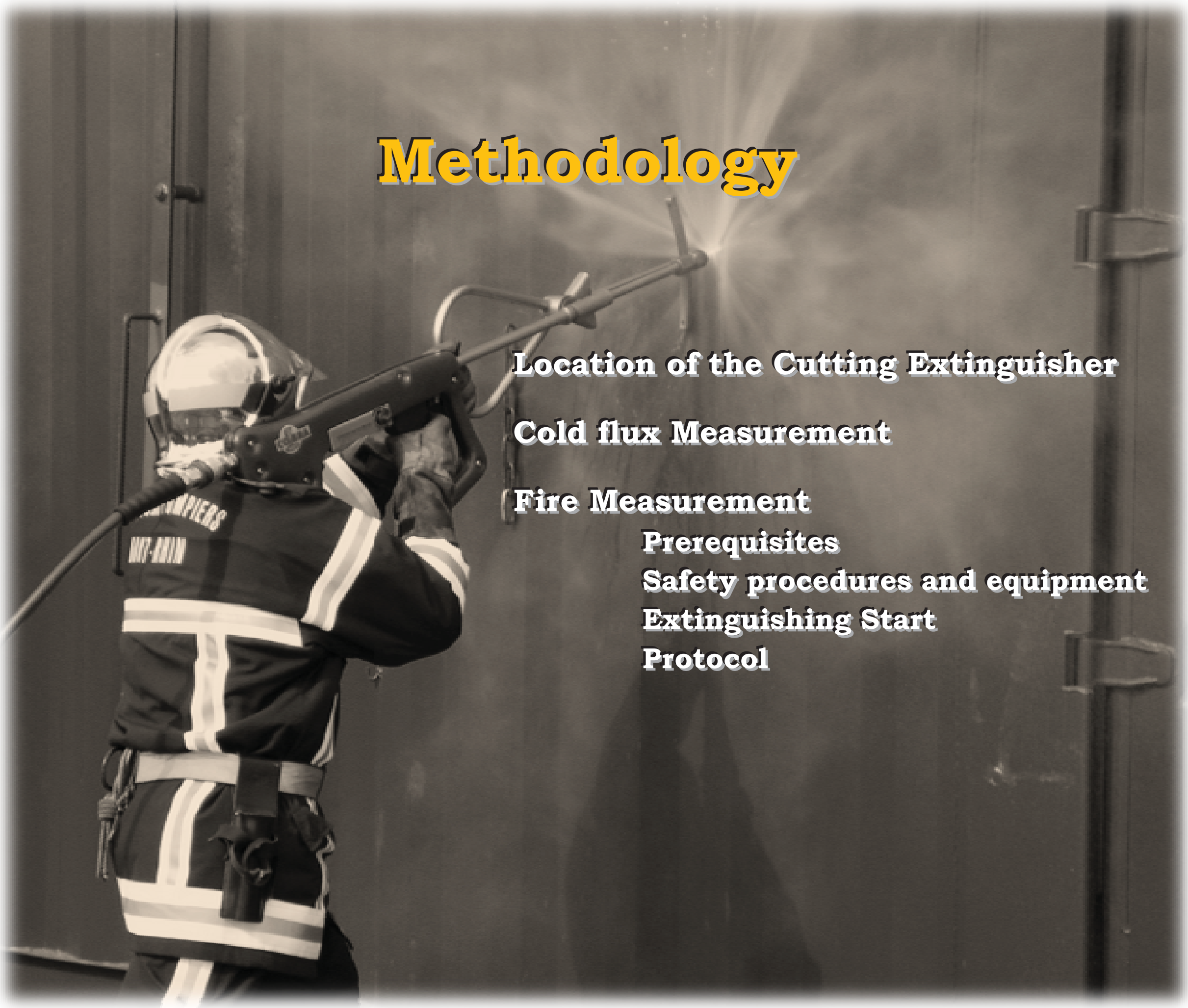
Figure 25. Camera positioning in the compartment, on the floor

- The camera n° 1 was used during the cold flux measurement; it is targeting the bottom wall.
- The camera n° 2 was used during fire experiment; it is targeting the bottom wall.
- The camera n° 3 was used during fire experiment; it is targeting the position where the jet is coming out of the wall
- The camera n° 4 was used during fire experiment; it is targeting the bottom wall.

In order to preserve the cameras as much as possible from heat, we always positioned them directly on the floor of the compartment.

Finally, in addition to all the installed apparatus, we also had one dedicated person constantly at the data logging place, who had the role of writing every noticeable change which may affect the records, including for example manipulation of the smoke vent, which would be responsible for temperature drops. The area reserved for this also needed to provide weather protection to the instruments. It was therefore either under a tent, or in a dedicated vehicle.

Figure 26. Data logging area; Left: Under the tent – Right: In a vehicle. Picture: Service Communication SDIS68


Methodology
Location of the Cutting Extinguisher
Cold flux Measurement
Fire Measurement
Prerequisites
Safety procedures and equipment
Extinguishing Start
Protocol

Methodology

The three weeks spent on the experimental field housing the compartment were very time limiting. The first week was dedicated to the “bottle frame” construction, and measurement, whereas the two other weeks were reserved for instrumenting the compartment, and building the mesh supporting the TC, and running the fire experiments. The following chapter describes the protocol used to carry out all the measurement, and the safety rules imposed.

Location of the Cutting Extinguisher

One of the guarantees of credibility of an experiment is its ability to be reproduced exactly how it has been run the first time. That is why we had to decide on a location of the Cutting Extinguisher, which would be the entrance point of the water mist, after having penetrated the compartment wall. The other issue is to always keep the same direction, avoiding changes of angles during the spraying.
And the third important point that has to be kept in mind is the desire to reproduce a fire extinguishing situation, like on a real intervention by fire fighters. Their tactical choice of operating location, angle and duration is learned from technical guides that are specific to the country, but which however are directly inspired from previous tests. They are then in accordance with the best possible location that would have been chosen by a scientist, resulting in a water mist action as efficient as possible.
The guidance for French fire fighters, as explained by Julien Gsell in a paper (The Cutting Extinguisher, presentation, demonstration, tactical and operational use, 2009 (10)) consist of applying the following consideration, with due regard to the fire situation:

- *If the fire is far, or undiscovered, focus the attack in the direction of the air vein feeding combustion.*
    - *Increases the distance of water mist travelling*
    - *Maximization of the extinguishing effect by heat extraction. The water mist is “sucked” by the flames, and travel then exactly in the combustion zone.*
    - *Avoids smoke and/or fire spread*
- *Attack trough the materials that are easy to penetrate (Windows, doors)*
    - *Faster drilling*
    - *Allows to change easily the jet direction*
    - *Is a guarantee of free space behind (no corridor or furniture behind)*
- *If the fire location is known, and it is possible to attack from a adjacent room, guide the jet in the upper part of the concerned enclosure*
    - *Note: only if there is no risk of smoke spread in the adjacent volumes.*
    - *Has a better cooling efficiency, since it is directly targeting the smoke layer*
    - *Is more secure, in the case of victims, who are closer to the floor*
- *Optimize the capabilities of the Cutting Extinguisher, by working in the length of the compartment*
    - *Avoids to strike another wall too close*
    - *Complete water mist formation after only 5 metres.*
- *Attack continuously, for a maximum of efficiency*
    - *There is no risk of burnings by overheated steam, since the attack is done from outside (different than “pulsing attack” with BA team and classical fog nozzle)*
    - *Faster temperature decrease*

- *Better inerting effect (oxygen depletion)*
- *Use infra-red (IR) camera, and if the building is complex, move to conduct an attack from several points*
    - *Allows a control of the action*
    - *Progressive attack, in order to weaken the fire, if it is too much developed to be tackled instantly*
    - *Global room cooling*
    - *Increased chances to reach the fire core, in case of "blind attack"*
- *Before attacking, close all the reachable openings*
    - *Avoids the outcome of combustion products, pushed by the gas flows generated by the velocity of the Cutting Extinguisher's jet*
    - *Saves the fire fighters from having an outcome of a sudden small fire ball (premixed flame created with the unburnt hot gases, and the air entrained by the jet)*
    - *Increases the inerting action*

In light of these requirements, we decided to attack the fire in the full length of the compartment. In order to have better water mist expansion, we chose the middle of the width. Finally, for the selection of the height and orientation, we choose 1.65 m and horizontal direction. (Standard height, since the fire fighter is carrying and attacking with the nozzle on its shoulder)

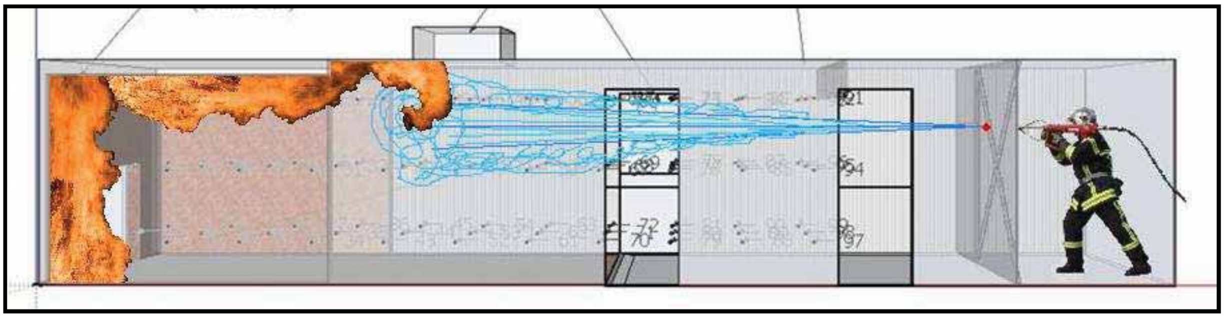


Figure 27. Point of Attacking fire (from outside fire room)

The inner wall being pierced by the Cutting extinguisher has been provided with a cylinder, playing the role of guide, in order to always keep exactly the same location, and only create one small hole. The orientation was checked by supporting the hose connection at the same point every time by a wedge fixed to the left wing, as shown on the picture.

Figure 28. Left & middle: First guide, later replaced by a steel cylinder / Right: Wedge used to preserve perpendicularity with the pierced wall [and then being exactly parallel with floor and vertical walls]. Picture: Service Communication SDIS68

The first hole was made before any measurement, to avoid any possible influence of the abrasive. Since this study is only focusing on the properties of the water mist, we only used the water trigger on the lance, spraying the water through the hole made previously.

Cold flux measurement

Due to a need to select the distance steps and the restricted time accorded to carry out the experiment, it was decided to construct the spray pattern on cross sectional area perpendicular to the jet direction, every 0.5 m. The furthest measurable distance is 10.0 m, because the plastic bottles need to have a short free space, when they are lifted by the spray. The closest is 2.00 m, which is the limit before tearing the bottles from the frame, due to the water velocity.

At 60 L/min, the Cutting Extinguisher has a reaction force (R) of 218 N, as calculated in previous section. If it is applied towards a surface, it is the core of the jet which is the vector of this force, which is then absorbed by the impacted surface (the impacted surface corresponding to the jet area, varying in function of distance).
The jet having an area (A) of 4.15 x 10^{-6} m^2 at the mouthpiece (With the diameter of the orifice of the nozzle being 2.3 mm), it has a force per unit area of:

$$F = \frac{R}{A} = \frac{218}{4.15 \times 10^{-6}} = 52.5 \times 10^6$$

$$F = \frac{R}{A} = \frac{[N]}{[m^2]}$$

At close range, the jet applies a thrust of 52.5 MN/m^2.

Basing use on the calculated diameter of the core of the jet, by Göran Holmstedt (The Cutting Extinguisher – concept and development p. 20, 1999 (6)), at 1 and 4 m, we can deduce it for 2 m, by interpolation:

$$\frac{furthest\ core\ diameter -\ closest}{furthes\ distance - closest\ distance} \times 2 = \frac{0.06 -\ 0.015}{4 - 1} \times 2 = \frac{0.09}{3} = 0.03\ m$$

Which then allows us to calculate the area of the core of the jet (impacted surface) at 2 m (A_2):

$$A_2 = \left(\frac{D_2}{2}\right)^2 \times \pi = \left(\frac{0.03}{2}\right)^2 \times \pi = 2.25 \times 10^{-4}\ m^2$$

The surface of the jet at 2 m being smaller than the area covered by a plastic bottle, we can deduce that the bottle is subjected to a thrust of 158 N (approximately $\frac{158}{9.81} 16.1\ kg$), which appeared to be the maximum sustainable thrust for a plastic bottle before getting torn by the steel wire which retains it.
For information, the force per unit area at 2 m is:

$$F_2 = \frac{R}{A_2} = \frac{218}{2.25 \times 10^{-4}} = 0.97 \times 10^6$$

Which corresponds to a thrust of approximately 99 tons ($\frac{0.97 \times 10^6}{9.81} 98878\ kg$) per square metre.

During the tests however, it appeared that the water jet was just passing between two bottle ranges; but it still had no ability to go closer, since the area of the spray is so small that the “bottle frame” was not collecting any water anyway.

Depending on the chosen scenario, the protocol followed the points below:

- Marking of the measuring distances on the floor
- Wedging the frame at the chosen distance
- Closing all the doors not remaining open, following the scenario
- Positioning of the fire fighter, and the Cutting Extinguisher in the guides.
- Continuous spraying during a specified time
    - 50 s, from 2 up to 3.5 m
    - 90 s, from 4 up to 6.5 m
    - 120 s, from 7 up to 10 m
- Measuring the amount of water collected per bottle, thanks to graduated cylinder (accuracy ± 1 mL), and emptying the bottles
- Taking note of the values recorded
- Moving the bottle frame at the next distance to measure, and wedging.

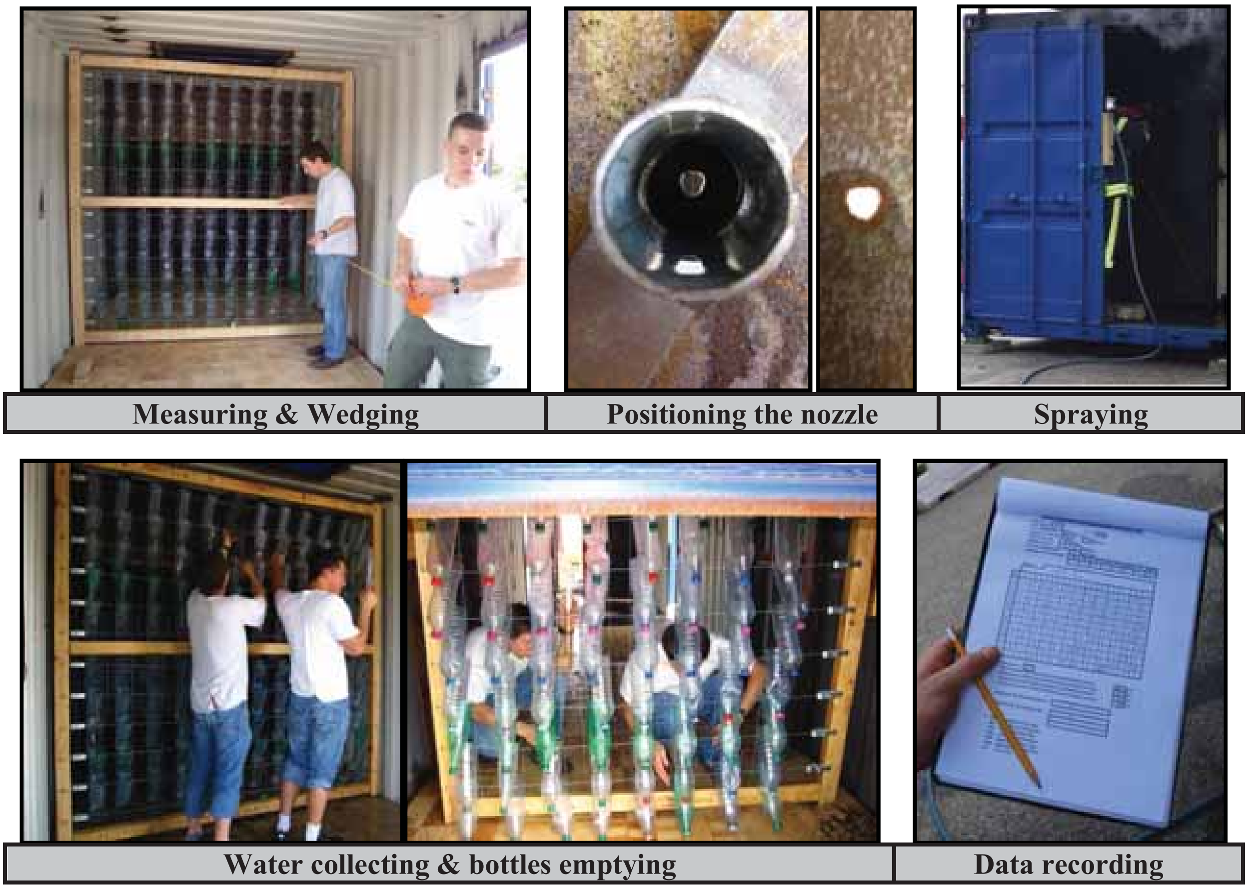


Figure 29. Water mist flux density measurement protocol

For safety reasons, the fire fighter using the Cutting Extinguisher had to wear his helmet with the visor down, and all the required equipment to operate. During spraying time, he was the only one in the restricted area around the compartment.

Fire measurement

Conducting a full scale fire experiment requires a minimum organization. Since the studied compartment is the property of the EDSP68, it is the Haut-Rhin Fire fighters School's responsibility to ensure safety during the burnings. Moreover, the fire behaviour training being a brand new part of the fire fighter's training program, during burning in the compartment all opportunities are taken to allow the fire trainers to observe the fire growth inside the compartment, and learn how to manage hot fire training within the compartment.
That is why we had two binding constraints to meet, namely, consider the fire fighter's staff training, and carry out the fire experiments only if the staff from the Haut-Rhin Fire fighters School were available to ensure safety.
The experimental protocol was then written and adapted to take into account the willingness of the School.

Prerequisites

From the experience of previous compartment fires, it is known that burning is not as efficient and impressive when the compartment remains humid, compared to a dry one. Attention was always paid to waiting enough time between two experiments, in order to allow the compartment to dry out. Even with this, the brick layer on the floor and the panels of combustible material retained moisture. The responsibility of the fire fighter managing the compartment was to manipulate the smoke vent in order to evacuate the steam generated when moisture starts to evaporate. The compartment needed also to be at ambient temperature. This observation prevented from carrying out more than one burning within the same day, in order to allow the compartment to cool down.
Concerning the instruments; the thermocouples were checked and re-protected or positioned before each burning. The broken were replaced, as long as we had spare ones. The data logger, and acquisition computer were subject to a control scanning.
The pressure transducers were also checked, as well as the radiometer, and the water cooling circuit was switched on.
The controls of the Cutting Extinguisher were examined and tested, with the same attention, including petrol refuelling, in order to be sure that it will run without being disrupted during extinguishing.

Safety procedures and equipment

Because there is always a danger when creating real fire, we considered the safety of the experiment with a special importance. The data logging area was far enough from the compartment, to be out of reach of the smoke gases coming out of the compartment. Excluding the fire fighter using the Cutting Extinguisher, at least two other fire trainers were in place, with fog nozzle at the ready. The restricted area was outlined by a white-red cord marking a perimeter of at least 5 metres around the compartment. Only fire fighters equipped with BA, and the entire protective equipment could encroach within this area while the fire was running.
After the experiments, staff were kept at the compartment surroundings as long as the boundaries were hot. At all other times, the doors were closed and locked, to ensure that nobody could enter (risk of carbon monoxide (CO) intoxication).

Extinguishing start

In a real fire situation, the time to extinguishing depends on the time taken by the Fire Brigade to arrive on scene. This time depends on the moment when the fire is detected, the alarm is raised and travel time. Typically, this gives us values ranged from 10 to 20 minutes.
In addition, the more developed a fire, the more difficult it is to extinguish. Since, in our case, the flashover, which is the evidence of all the fuel being involved in the fire, needs less than 10 minutes to occur, the worst case scenario was taken, meaning that the lower limit of 10 minutes and attaining flashover stage was largely exceeded.
So, in order to define a precise moment for extinguishing, three possibilities were studied:

- Require a minimum temperature of the smoke layer (550 °C for example) on a defined TC.
- Wait until visible rollovers coming out of the compartment.
- Use a target fuel, far enough from source fire to avoid ignition step by step fire progress (A cardboard box, back from the fire area, standing on the floor for example). When it ignites, it means the surrounding is hot enough, and the extinguishing can start.

Since we also had to cope with the fire fighters training inside the compartment, and remaining in it even after flashover stage, it was not possible to act as a sprinkler head would react, i.e. turn on once a defined limit temperature is reached. Moreover the two last propositions are too random to constitute a reliable basis.
That is why, we chose the first solution, but with a notion of **minimum required temperature**, instead of **limiting temperature**. In other words, this means that we selected the TC 11 (located at 1.20 m from bottom, 0.40 m under ceiling, and middle position regarding to left-right walls), and followed its temperature evolution on a graph. Extinction could occur during the stage of 770°C reached or exceeded, and before fire decay. The time interval then allowed the required flexibility for the fire fighter's training inside to complete their observation, go out and away from the compartment, before the start of extinguishing.

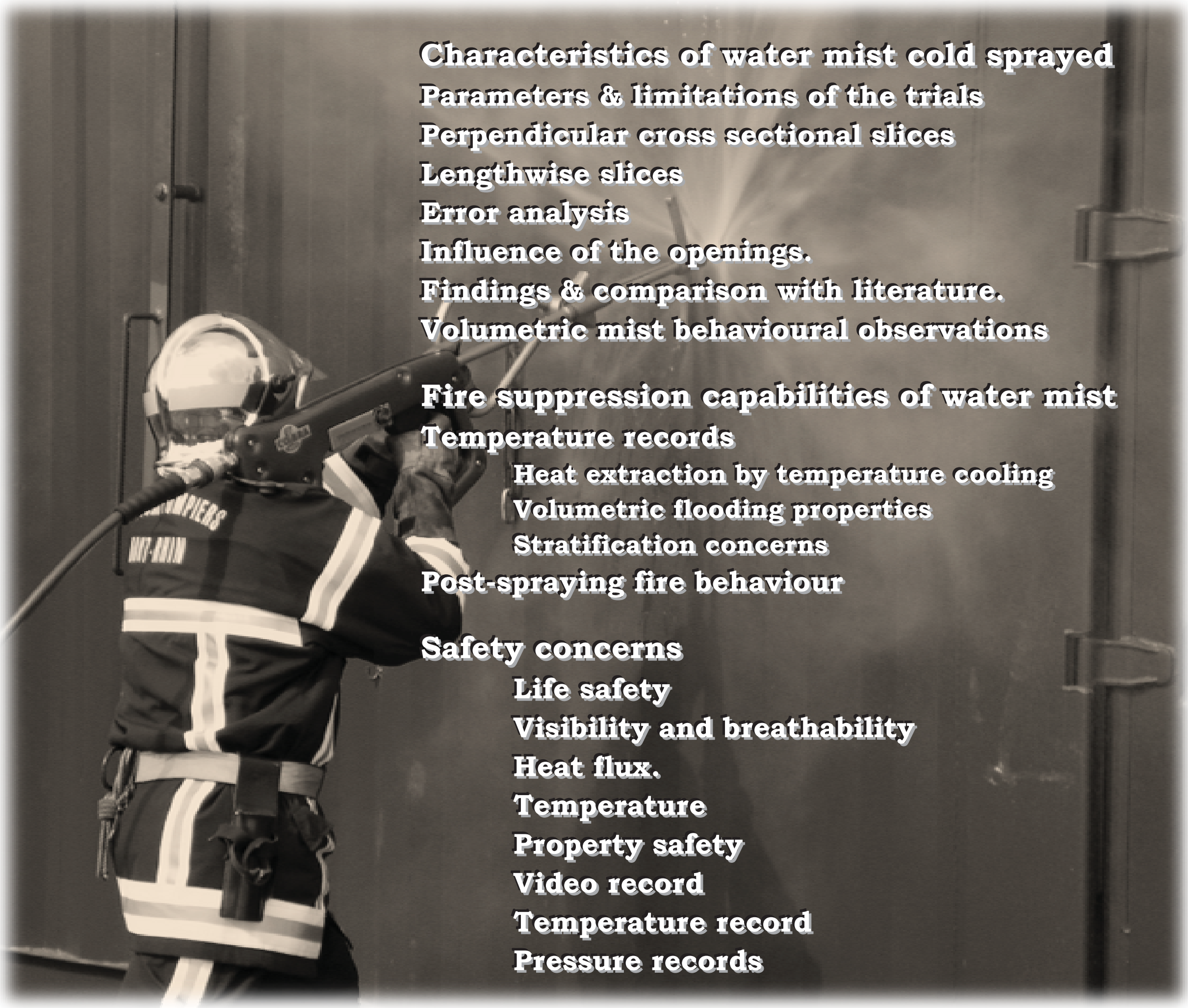
Protocol

The minimum imposed number of persons concentrating only on the experiment was two. One fire fighter using the Cutting Extinguisher, and one assigned to checking the data logging and evolution of the parameters during the fire evolution.
In chronological order, the actions were taken as follow:

- Before ignition
  - Prerequisite checking
  - Apparatus powering, and instruments connecting
  - Establishment of combustible panels
  - Closing of all the unused openings (the air feeding of the fire being later controlled by the compartment operator, only with the main entrance door)
  - Deployment of the Cutting Extinguisher (after prerequisite checking)
  - Alimentation in water of the Cutting Extinguisher
  - Closing of the left wing, to prepare the orientation guide
- Firing
  - Start of all the recording apparatus
  - Checking of the water cooling circuit of the radiometer
  - Ignition

    - ➢ Starting of the Cutting Extinguisher's engines
    - ➢ Checking that all the staff members in the restricted area are wearing the required protective equipment and BA.
- Extinguishing
    - ➢ Temperature growth at least until reaching 770 °C on TC 11, and before decay
    - ➢ Checking nobody remains in the compartment
    - ➢ Closing the door used for air feeding
    - ➢ Extinguishing start: 3 minutes spraying, non-stop
    - ➢ Waiting 3 more minutes, without any change on the compartment
- End of the experiment & rehabilitation
    - ➢ Stopping the recordings and saving data
    - ➢ Compartment self cooling
    - ➢ Apparatus cut-off
    - ➢ Rehabilitation of all the materials and equipment used

Results


Characteristics of water mist cold sprayed
Parameters & limitations of the trials
Perpendicular cross sectional slices
Lengthwise slices
Error analysis
Influence of the openings.
Findings & comparison with literature.
Volumetric mist behavioural observations
Fire suppression capabilities of water mist
Temperature records
Heat extraction by temperature cooling
Volumetric flooding properties
Stratification concerns
Post-spraying fire behaviour
Safety concerns
Life safety
Visibility and breathability
Heat flux.
Temperature
Property safety
Video record
Temperature record
Pressure records

Results

Within three complete weeks having a Cutting Extinguisher loaned by the company Fire Technologies, 25 cold flux cross sectional measurement has been realized, and 8 burnings. Because of many unpredictable events, which are inevitable in such a short time, we have a real total of successful experiments of 20 cold flux measurements, and 5 burnings.

Characteristics of water mist cold sprayed

As mentioned very briefly in the protocol, the first five experiments have not been taken into account due to the deflector effect generated by the central beam of the "bottle frame", filling the bottles of the under row mostly thanks to the jet influence. The beam has been removed, and the experiments restarted, for 20 trials.

Parameters & limitations of the trials

From this point in the report, the distances of perpendicular cross sectional views given are always taken from the position of the mouthpiece of the Cutting Extinguisher.

On these 20 trials, all the distances from 2.0 m up to 10.0 m were measured, with a step of 0.5 m, for a total of 17 positions. During all the tests, the compartment was completely closed, except at the distance of 4.5 m where both closed and open compartments were tested, following the two possible scenarios detailed in the section dealing with the compartment characteristics. As a reminder, the scenario with openings consists of keeping completely open the door n°2, and the upper pane n°4 (representing a forgotten door, and an open window)

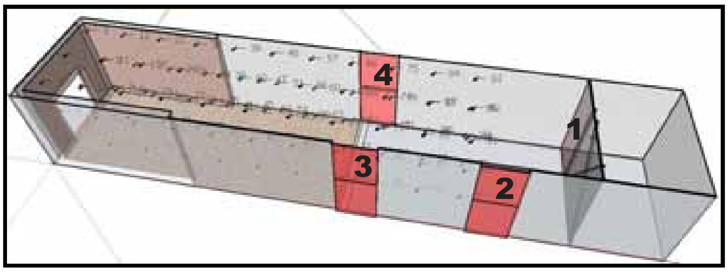


Figure 30. Location of the openings of the compartment

Since we did not have time to repeat all the distance tests with both open and closed compartments, the 4.5 m distance was selected since the frame is at the height of the "window" n°4. This point could have the strongest influence at this position, and also because it is the last point before reaching the break up distance of 5 m found by Holmstedt, and Bjerregaard & Olsson in their studies (8).

The two last distances were used to check the accuracy of the results, in comparing the differences, when measuring both times at the same point. The selected distances for repeatability checking were 7.0 and 9.0 m.

Regarding the precision of water collecting now, we considered that due to all the factors outlined previously, and the precision of the graduated cylinder, we did not considered the water amount (W_a) as being negligible if it is less than 8 mL per bottle. Since the shortest spraying time (T_p) was 50 s, the negligible flow rate (N_f) per bottle is:

$$N_f = \frac{W_a}{T_p} = \frac{8}{50} = 9.6\ mL/min$$

Converted to the water amount per square metre (N_{f^2}), thanks to the area of a bottle ($A_b = 56.7\ cm^2$), it gives:

$$N_{f^2} = \frac{N_f}{A_b} = \frac{0.0096}{0.00567} = 1.69\ L/min.m^2$$

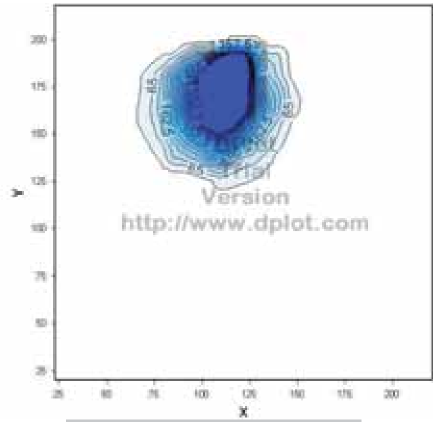
We then disregard the flow surface lower than 1.69 L/min.m^2, or 28 mL/s.m^2.

Last noticeable remark, the cross sectional views from 7.5 m from the nozzle seem to have been narrowed. That is due to the fact that as we enter the fire zone, "bottle frame" was reduced in size in order to fit in the smaller space (due to CorTen steel dubbing).

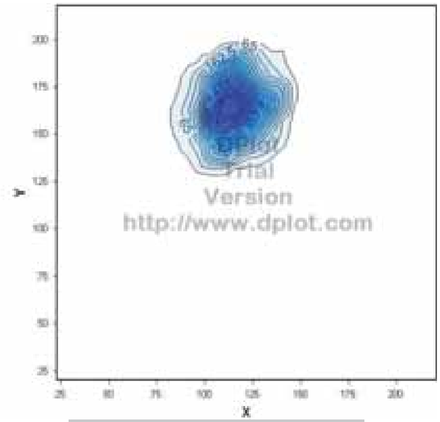
Perpendicular cross sectional slices

The preferred way to exploit data is to show the water density, in mL/s.m^2, at several distances from the nozzle. It allows catching a lot of information purely by visual means. The following figures then show the cross sectional views of the spray, measured with the "bottle frame", in function of distance. Precisely, the last ISO surface represents a flow rate per unit area of 32.5 mL/s.m^2, which corresponds to 1.95 L/min.m^2; it is then higher than our lower negligible limit (1.69 L/min.m^2)

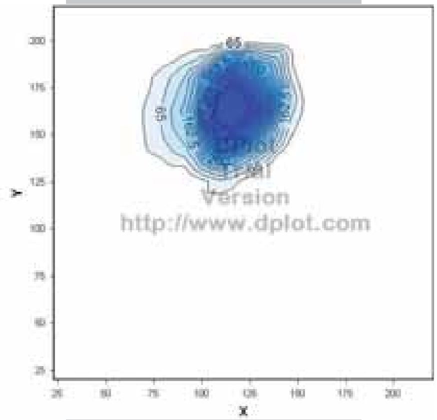
<u>Cutting Extinguisher's spray pattern, in function of the distance from the nozzle</u>



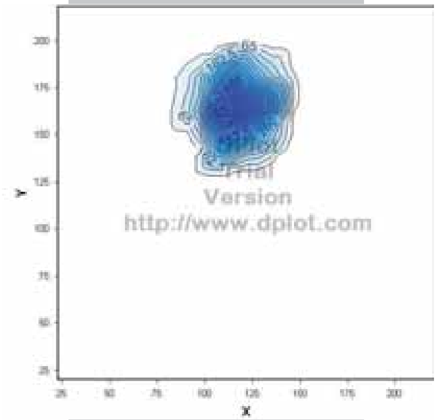
At 2.0 m from the nozzle



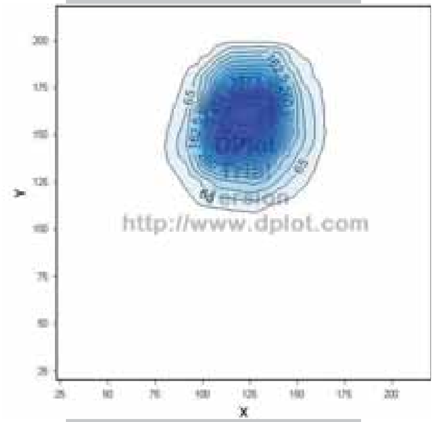
At 2.5 m from the nozzle



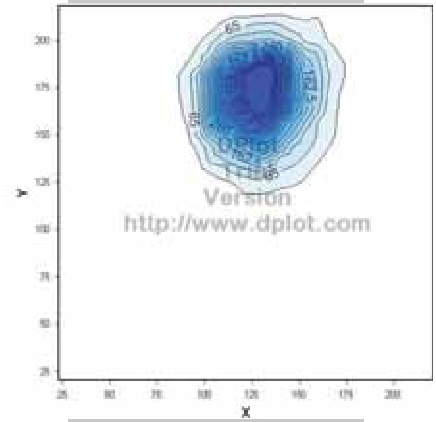
At 3.0 m from the nozzle



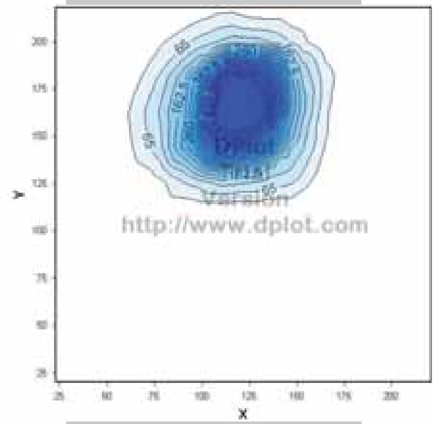
At 3.5 m from the nozzle



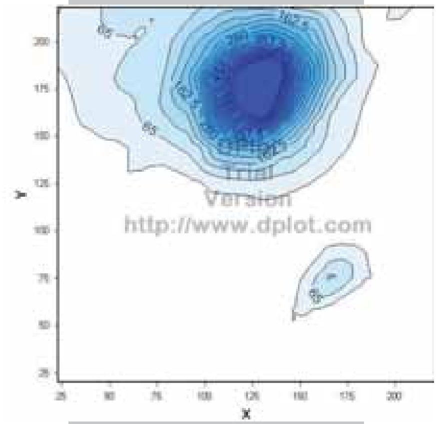
At 4.0 m from the nozzle



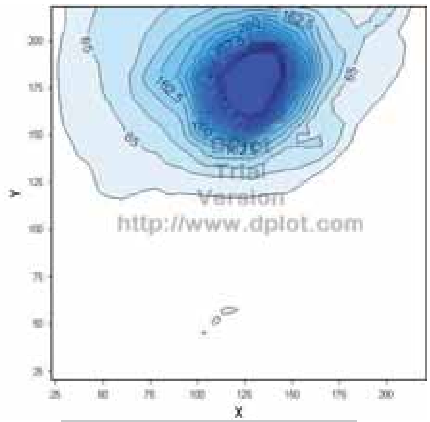
At 4.5 m from the nozzle



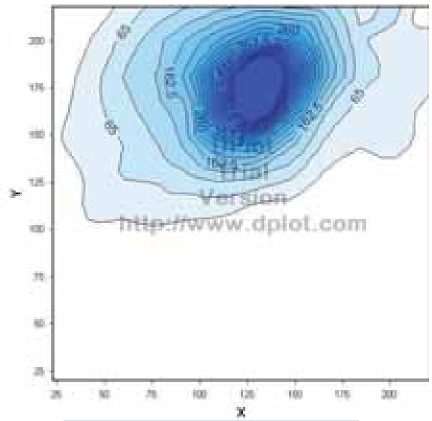
At 5.0 m from the nozzle



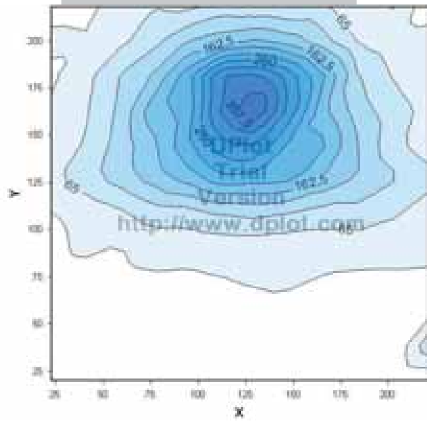
At 5.5 m from the nozzle



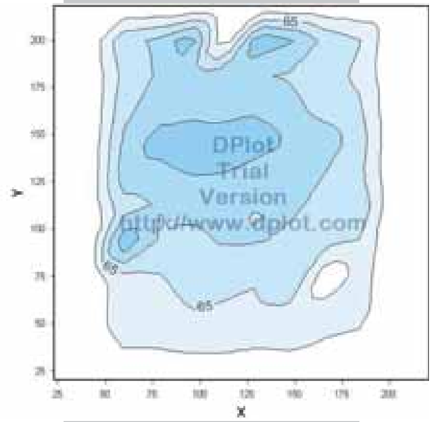
At 6.0 m from the nozzle



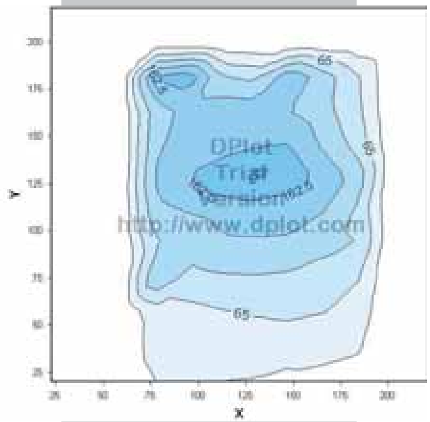
At 6.5 m from the nozzle



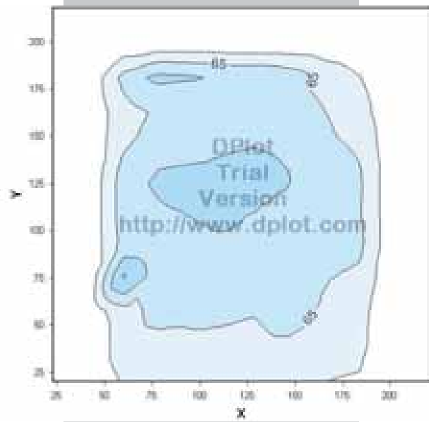
At 7.0 m from the nozzle



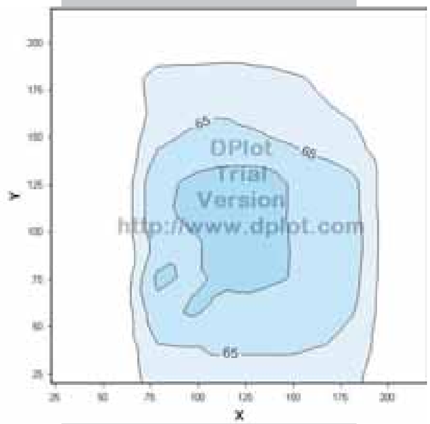
At 7.5 m from the nozzle



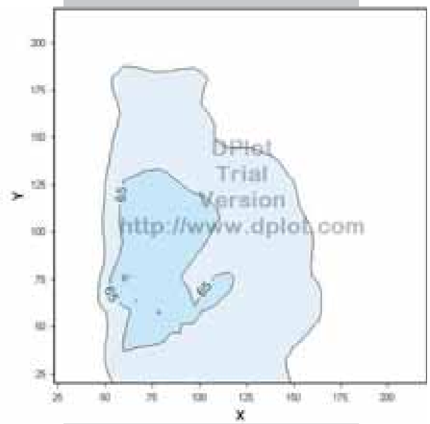
At 8.0 m from the nozzle



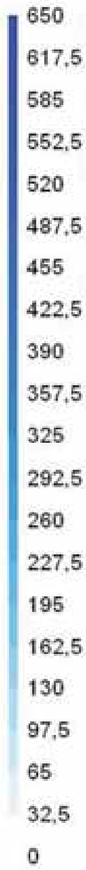
At 8.5 m from the nozzle



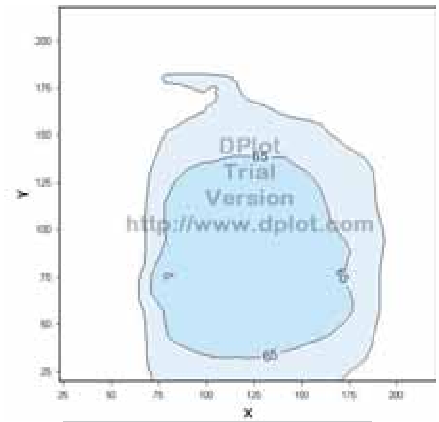
At 9.0 m from the nozzle



At 9.5 m from the nozzle



$mL/s.m^2$



At 10.0 m from the nozzle

Figure 31. Cutting Extinguisher's spray pattern on cross sectional slices, in function of the distance from the nozzle

At first sight of the patterns, it appears that the inner core of the jet seems to be very variable. This typically shows a limitation of the "bottle frame", since the inner core has a much lower area than the surface covered by a bottle, until it break up completely. However, it is still possible to estimate the diameter of the outer ring formed by the water mist.

Lengthwise slices

Using the values found at the closest distance from the centreline of the jet, we could try to represent a lengthwise cross section of the jet. However, the location of the vertical rows of bottles from the left wall are either at 1.13 or 1.31 m, if we take the closest from the distance at which the jet is passing, which is 1.20 m.

The one at 1.13 is then at 0.07 m from the centreline, further enhanced to 0.11 m for the row at 1.31 m. Using the same scales (in mL/s.m^2), and mode of representing the flow rates, it gives the following pictures:

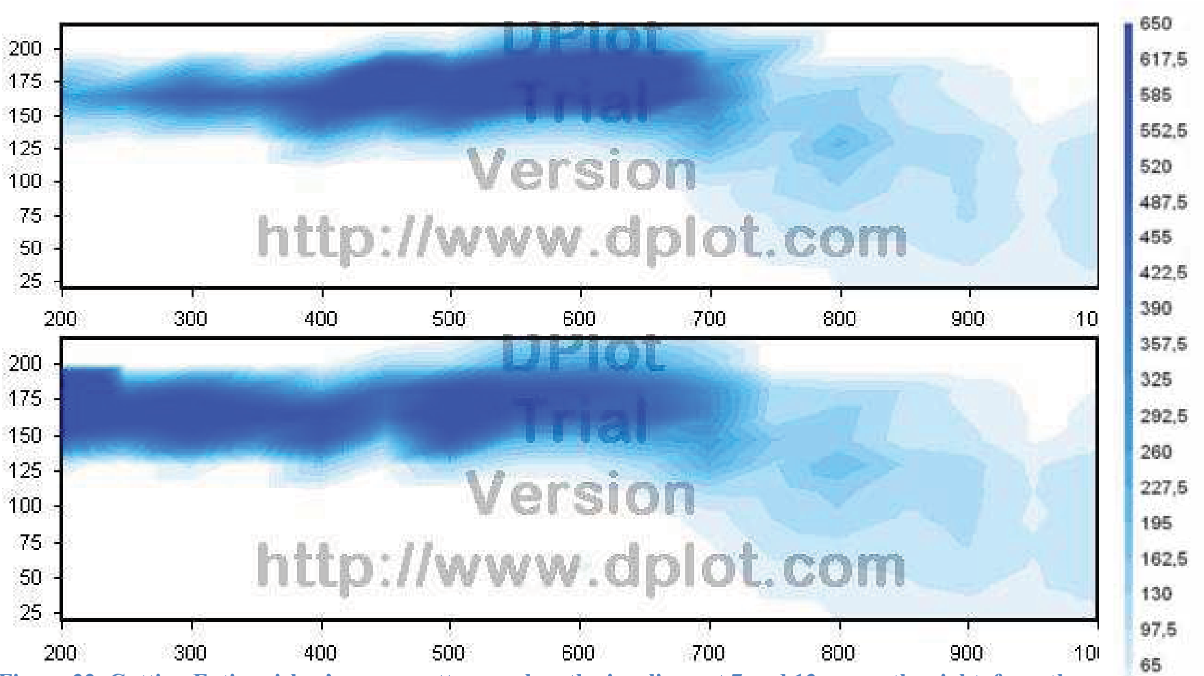


Figure 32. Cutting Extinguisher's spray pattern on lengthwise slices, at 7 and 13 cm on the right, from the centreline of the jet

One of the immediate remarks that could be mentioned is the better view of the lengthwise slice at 7 cm, which appears to be logical since it is closer to the centreline than the other one. Using this one allows us to compare several basic details given in the literature (regarding the shaping and pattern of the spray), which will be the aim of a later section.

In reversing horizontally the figure obtained, and integrating the measured plan in the compartment, taking into account the proportions, we get the following stitching:

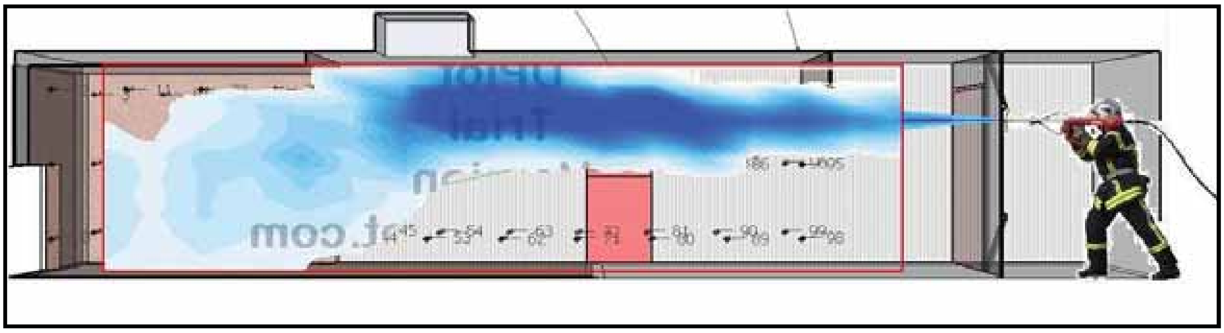


Figure 33. Cutting Extinguisher lengthwise spray pattern (in the red rectangle), integrated in the concerned compartment

Error analysis

Regarding the precision of our measurement, we can calculate the variation coefficient thanks to an error analysis in comparing some tests repeated exactly in the same manner.
The defined limits of accuracy are chosen at $\pm$ 25 mL/s.m^2 ($\pm$ 1.5 L/min.m^2), which is smaller than the lower limit of recording (1.69 L/min.m^2)
This would check the accuracy for two perpendicular slices measurements:

- At 7.0 m from the mouthpiece:
  We can see that comparing the records on the basis of a delta of $\pm$ 25 mL/s.m^2 gives us 7 values exceeding the limit.

-7,3	-2,9	-2,9	2,9	-4,4	4,4	-17,6	-5,9	-5,9	-11,7	-8,8	-32,3
-7,3	5,9	8,8	13,2	8,8	0,0	-2,9	-11,7	-5,9	-8,8	-2,9	-20,6
2,9	5,9	10,3	13,2	22,0	13,2	-13,2	-35,2	-19,1	-5,9	-5,9	-11,7
10,3	4,4	11,7	44,1	35,2	8,8	-52,9	-41,1	2,9	-8,8	-2,9	5,9
11,7	8,8	10,3	11,7	19,1	0,0	-29,4	-23,5	-17,6	-2,9	2,9	-19,1
23,5	0,0	8,8	22,0	19,1	19,1	10,3	-5,9	2,9	-2,9	4,4	-4,4
5,9	-1,5	-4,4	11,7	-13,2	16,2	14,7	8,8	2,9	8,8	4,4	-2,9
-2,9	2,9	-5,9	0,0	-2,9	4,4	10,3	7,3	8,8	8,8	5,9	8,8
-2,9	-2,9	-11,7	0,0	1,5	8,8	8,8	10,3	2,9	-17,6	8,8	8,8
0,0	0,0	13,2	0,0	-14,7	-5,9	1,5	0,0	0,0	-5,9	0,0	2,9
0,0	0,0	0,0	-17,6	-23,5	-14,7	-14,7	0,0	0,0	11,7	0,0	17,6

Table 3. Differences of water flow rate per unit area, for different measurements at the 7.0 m, the red boxes are showing the number of bottles having a delta exceeding 25 mL/s.m^2

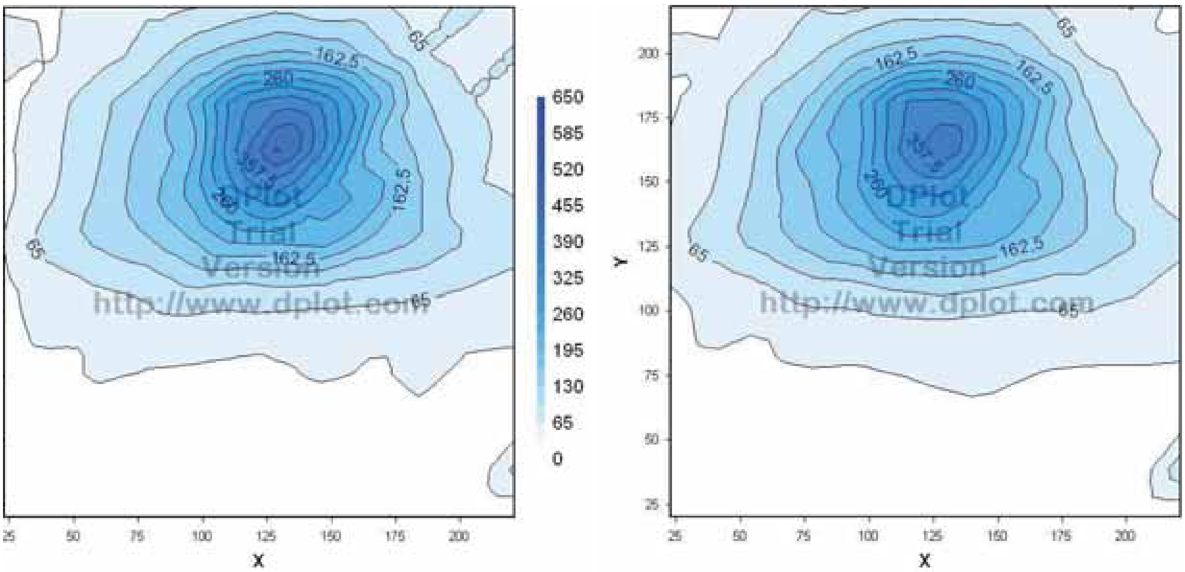


Figure 34. The 2 spray patterns showing the water flow rate per unit area at 7.0 m are quite identical

$$Rate\ of\ error = \frac{100}{tot.measured\ n°\ of\ btles} \times n°\ of\ btles\ exceeding\ limit = \frac{100}{144} \times 7 = 4.86\ \%$$

➔ From here we can conclude that more than 95 % (rate of accuracy) of the measured have a precision of $\pm$ 25 mL/s.m^2

- At 9.0 m from the mouthpiece:
  We can see that comparing the records on the basis of a delta of $\pm$ 25 mL/s.m^2 gives us 2 values exceeding the limit.

0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	-27,9	-13,2	-0,7	-11,0	-7,3	0,0	1,5	0,0	0,0
0,0	0,0	0,0	-14,0	-13,2	-13,2	-10,3	16,9	17,6	-1,5	0,0	0,0
0,0	0,0	0,0	-5,1	-8,8	-2,9	-8,8	-13,2	-2,2	-0,7	0,0	0,0
0,0	0,0	0,0	-0,7	-9,5	-22,0	-20,6	-9,5	2,2	10,3	0,0	0,0
0,0	0,0	0,0	-2,2	-0,7	-8,8	-19,1	-9,5	6,6	8,1	0,0	0,0
0,0	0,0	0,0	-4,4	-0,7	0,7	2,2	3,7	5,9	7,3	0,0	0,0
0,0	0,0	0,0	-0,7	5,1	11,0	14,7	15,4	17,6	15,4	0,0	0,0
0,0	0,0	0,0	14,7	26,4	19,8	16,9	16,2	24,2	20,6	0,0	0,0
0,0	0,0	0,0	5,1	5,9	11,0	16,2	19,1	16,9	12,5	0,0	0,0
0,0	0,0	0,0	17,6	25,0	17,6	15,4	18,4	19,1	13,2	0,0	0,0

Table 4. Differences of water flow rate per unit area, for different measurements at the 9.0 m, the red boxes are showing the number of bottles having a delta exceeding 25 mL/s.m^2

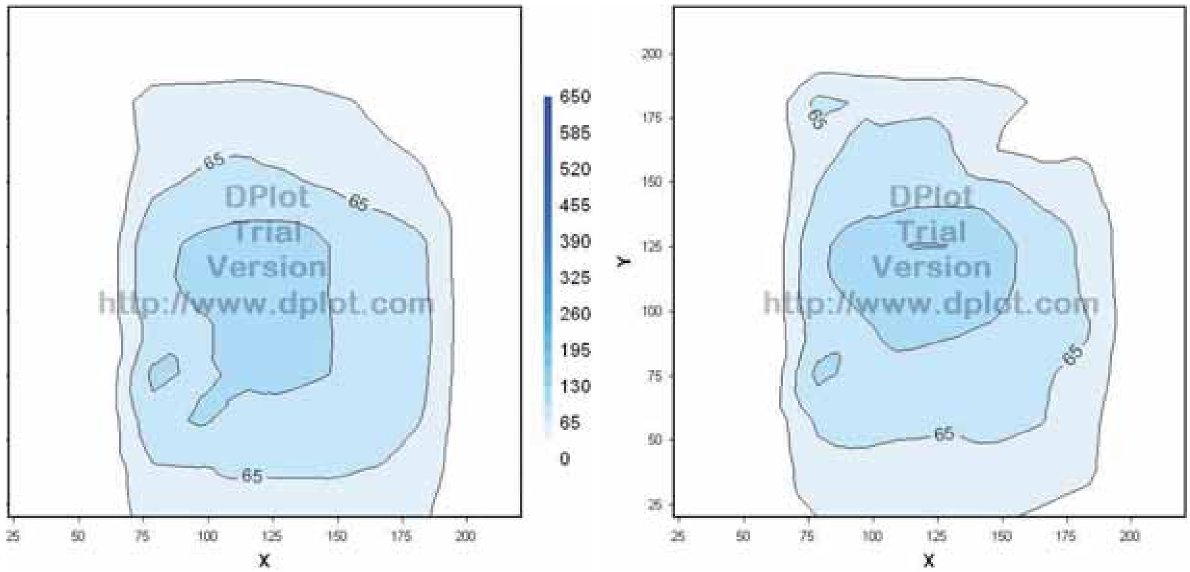


Table 5. The 2 spray patterns showing the water flow rate per unit area at 9.0 m

They look very similar, excepting the small differences on the top right corner

$$Rate\ of\ error = \frac{100}{tot.measured\ n^\circ\ of\ btles} \times n^\circ\ of\ btles\ exceeding\ limit = \frac{100}{70} \times 2 = 2.85\ \%$$

➔ From here we can conclude that more than 97 % (rate of accuracy) of the measurements have a precision of $\pm$ 25 mL/s.m^2

Regardless of the measuring distance, all the recorded values have a rate of error lower than $\pm$ 25 mL/s.m^2 ($\pm$ 1.5 L/min.m^2) for more than 95 % of the sample.

Influence of the openings.

As mentioned earlier, and since the fire scenarios will take due regard of openings, at least one of the perpendicular cross sectional water flow measurements have been conducted with the compartment being "open". The selected distance was 4.5 m.
In order to see if having some openings (reminder: the leakage area with compartment closed is $A_c = 0.192$ m^2, whereas when the selected doors are open, it increases to: $A_o = 2.71$ m^2) influences the water mist creation and expansion, we estimate the difference of flow rate per unit area at each control surface represented by a bottle. Based on the data used for the error analysis, the influence is considered being significant if more than 5 % on those that collected water have a rate of error higher than $\pm$ 25 mL/s.m^2.

0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	-11,7	29,4	39,2	27,4	0,0	0,0	0,0	0,0
0,0	0,0	0,0	-15,7	-31,3	43,1	219,3	31,3	21,5	0,0	0,0	0,0
0,0	0,0	0,0	-23,5	-47,0	-78,3	0,0	-11,7	5,9	0,0	0,0	0,0
0,0	0,0	0,0	0,0	-70,5	-164,5	-129,2	-43,1	-5,9	0,0	0,0	0,0
0,0	0,0	0,0	0,0	-19,6	-50,9	-27,4	-21,5	-17,6	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	-19,6	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table 6. Differences of water flow rate per unit area, for closed or open compartment scenario at 4.5 m; the red boxes are showing the number of bottles having a delta exceeding 25 mL/s.m^2

$$Rate\ of\ error = \frac{100}{tot.measured\ n°\ of\ btles} \times n°\ of\ btles\ exceeding\ limit = \frac{100}{29} \times 15 = 51.7\%$$

Over 29 bottles which collected water on both trials, more than the half of them (15) contained water showing flow rate differences of more than $\pm$ 25 mL/s.m^2, which means undoubtedly that the openings do have an influence on the spray behaviour.

We can also notice that the control surface represented in green does not change, regardless to the presence or not of openings, having a value of 724.5 mL/s.m^2 on both tests. This can be explained by the location of the control surface, (its centre is at 1.31 m from left wall, and 1.64 from the floor, and the jet central axis is estimated as passing at 1.20 m from left wall and 1.65 m from floor), since the proximity of the core means water displacement at high velocity, thereby less affected by the possible perturbations of the air streams with openings.

Based on the positive or negative differences on the significant location, we cannot outline any clear tendency of water mist behaviour change, excepting that the variations are affecting the immediate surrounding ring, possibly by creating a whirling vortex of mist around the core, which has been observed during the tests.

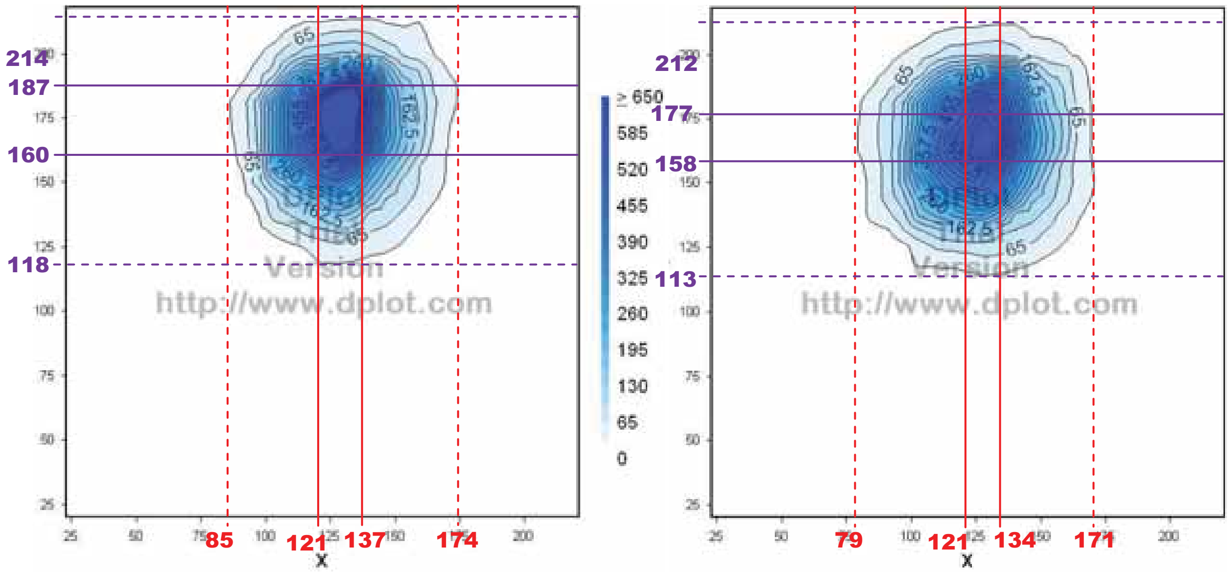


Figure 35. Left: spray pattern at 4.5 m without opening -. Right: at the same distance with openings. Measurement of the height and width of the core and outer ring

On observing the spray pattern, however, some other changes are noteworthy, by measuring the height and width of the core (taken as having a higher flow rate per unit area than 650 mL/s.m^2) of the jet and the outer ring of mist (having a higher flow rate per unit area than 32.5 mL/s.m^2):

- Without openings:
  - Inner core height: $Hc_c = 187 - 160 = 27\ cm$
  - Inner core width: $Wc_c = 137 - 121 = 16\ cm$
    - Surface: $Sc_c = 27 \times 16 = 432\ cm^2$
  - Outer ring height: $Hr_c = 214 - 118 = 96\ cm$
  - Outer ring width: $Wr_c = 174 - 85 = 89\ cm$
    - Surface: $Sr_c = 96 \times 89 = 8544\ cm^2$

- With openings:
  - Inner core height: $Hc_o = 177 - 158 = 19\ cm$
  - Inner core width: $Wc_o = 134 - 121 = 13\ cm$
    - Surface: $Sc_o = 19 \times 13 = 247\ cm^2$
  - Outer ring height: $Hr_o = 212 - 113 = 99\ cm$
  - Outer ring width: $Wr_o = 171 - 79 = 92\ cm$
    - Surface: $Sr_o = 99 \times 92 = 9108\ cm^2$

The inner core seems in both situations to be a little elongated vertically, probably due to the influence of gravity on the weight of the heaviest droplets starting to break away from the central water beam. The width has a value of 59% of the height without openings, and 68% with. However, the real change is on the surface of the core. With openings, the core is reduced by 30% in height and 19% in width, which means a surface reduced by 43%, whereas the outer ring is increased by only 6%, which is quite low, or negligible.

➔ In the light of these findings, we can conclude the water mist produced by the Cutting Extinguisher within a closed enclosure remains longer assembled in a central water beam with a ring of droplet cluster rather sparse; whereas in the case of openings, the jet tends to have a smaller inner core, but a much denser ring of droplet cluster. This phenomenon could be explained whether we assume the opening are creating stronger air flows disturbing in this the spray development, and generating by this way greater drag forces at the boundary of the core. The water beam then loses its cohesion on its circumference, causing a detachment of water particles, which are sucked with the air entrained at the wake of the beam.

Findings & comparison with literature.

Mentioned both in the work of G. Holmstedt, J. Bjerregaard & D. Olsson (8) or the MSB in its "Cutting Extinguishing Concept – practical and operational use –", the break up distance of the water jet is a major parameter, which is necessary to take into account because of its implication on the efficiency of the extinguishing, regarding the compartment shaping.
All the scientists agreed on the start of the mist break up at a distance of 5.0 metres, and a mist fully developed when the length of 7.0 metres is reached.
By looking at the perpendicular slices, we can confirm these results:

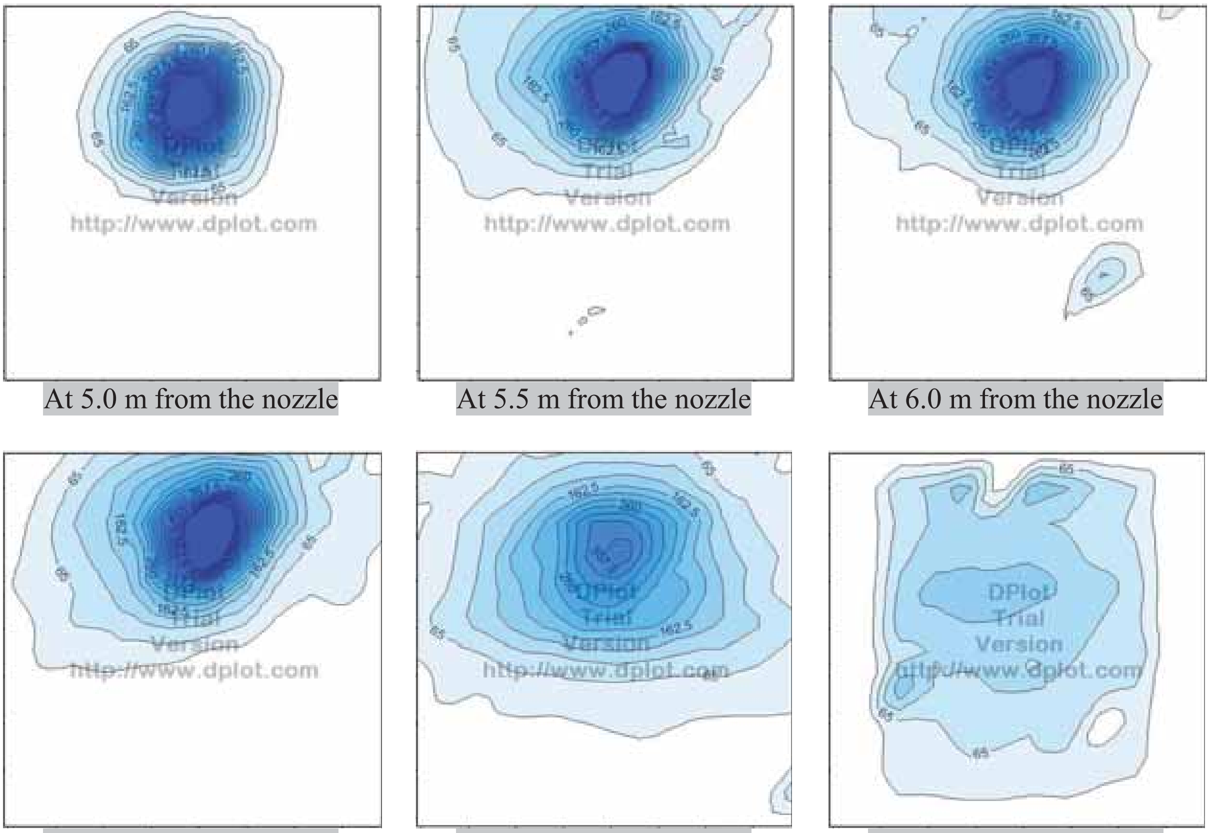


Figure 36. Cutting Extinguisher's spray pattern on cross sectional slices, from 5.0 up to 7.5 m from the nozzle

Until 5.0 m, the ISO surfaces remain very circular, with an inner core having a higher flow rate per unit area than 650 mL/s.m^2, and an outer ring composed of water mist of decreasing density with increasing distance from centreline. At 5.5 m, the droplet cluster loses its ring shaped pattern, and tends to rise relative to the position of the inner core. At 7.0 m, there is no more inner core, the jet has completely broken up, and all the water is now split into droplets. The cloud however still keeps a sort of cohesion around a denser central ring of water mist. And at 7.5 m the mist cloud is completely dispersed, taking all the available surface of the cross sectional plan; there is no more central core.

On a lengthwise slice at 7 cm left from the centreline of the jet, the break up phenomenon, changing to water atomisation is also visible on the figure below: Both inner core and outer ring keeps integrity until 5.30 m from the nozzle. After this point, the outer ring disappears to make room for an expanding droplet cloud, until the inner core splits up too, at 6.85 m. Final step of the mist expansion, at 7.45 m, due to absence of inner core and decrease of velocity, the cloud of water mist finishes expanding by taking all the volume of the compartment.

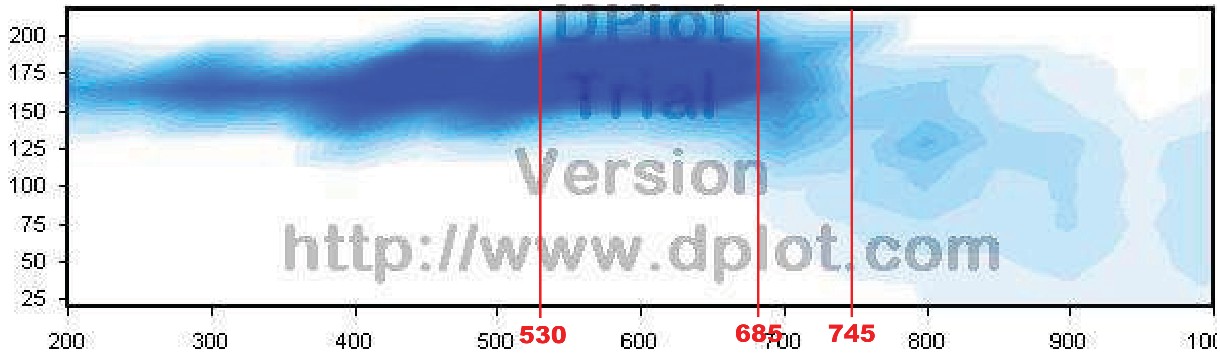


Figure 37. Evolution of the water jet into mist on lengthwise slice, with major steps of mist formation

The diameter of the spray (considering in this case both inner core and outer ring) is an important parameter, which allows further calculations, especially on cooling capability of the water mist. We will base the research on the ISO surfaces obtained on the perpendicular cross sectional slices.

Since we stated earlier that the final step of water mist expansion occurs at 7.45 m (where mist and air are moving at the same speed, and has no more cohesion around a central high velocity core), we could expect to still have a measurable surface at the last cross sectional measurement, which is at 7.0 m. The first ring, being pseudo cylindrical at this distance, is the one representing a flow rate per unit area of at least 100 mL/s.m^2 (6 L/min.m^2). We will then take this value as a reference for our ring diameter measurements.

Basing ourselves on the literature, and especially the results of Bjerregaard and Olsson (2007), we suppose the spray to expand as a conical pattern of determined angle, until the break up point, and a wider angle after this point. So, with a break up point found at 5.30 m, and in order to have sufficient values, we do the measurements at 3.5, 4.0, 4.5 and 5.0 m for the slices before break up. For those after this 5.30 distance, we take 5.5, 6.0, 6.5 and 7.0 m.

We do not take into account the first and last distances, since there are probable errors of water collecting because of a too high velocity on one side, and the limitations of recording due to “bottle frame” narrowing from 7.5 m.

The values are taken by measuring preferably the largest distance covered on horizontal plan by the 100 mL/s.m^2 ISO surface, rather than vertical, since they are not disturbed by the ceiling.

The data is measured in **Appendice A2**, and summarized in the following table:

Distance	m	3.5	4	4.5	5	5.5	6	6.5	7
Diameter	m	0.54	0.64	0.66	0.82	0.98	1.15	1.21	1.52
Radius	m	0.27	0.32	0.33	0.41	0.49	0.58	0.61	0.76

Table 7. Geometry of the jet, depending on the distance from the mouthpiece, based on experimental measurement

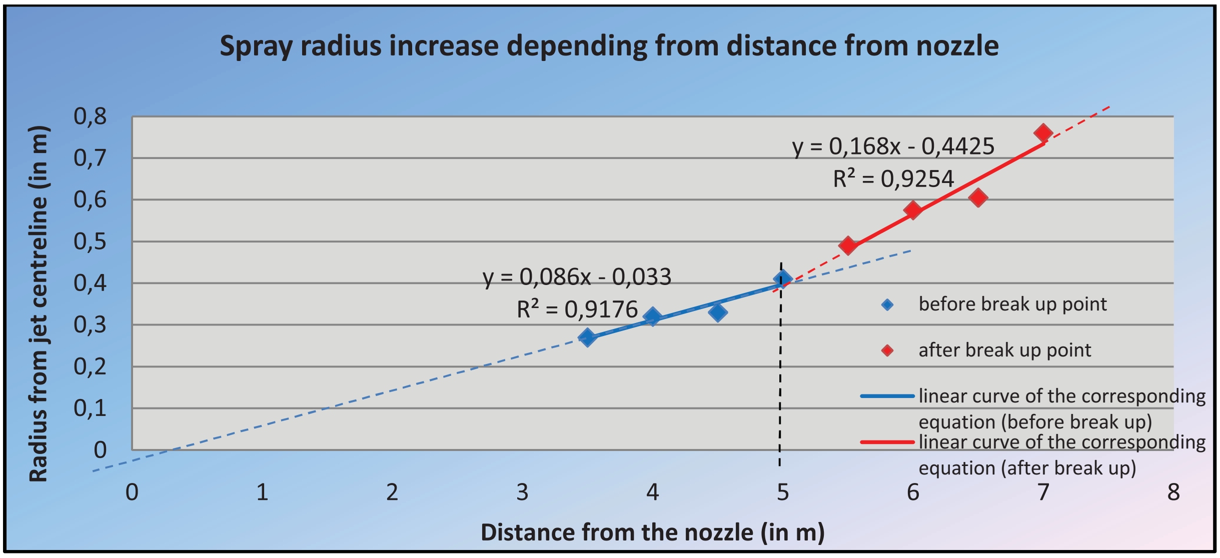


Figure 38. Determination of linear representation of the radius of the water mist ring, before and after the break up point

From the graph we can see that the ring of water mist is following a linear evolution in function of distance, until the break up point, where the slope is increased. The intersection of the two curves happens just at 5.0 m (at 4.94 m from nozzle, for a radius of 0.39 m).
Correcting the equation of linear representation to make the radius having a zero value at point blank (neglecting the radius of mouthpiece orifice at 1.15 mm), we get:

$$r_b = 0.0784 \times distance\ from\ nozzle$$

With a determination coefficient being still over 90% ($r^2 = 0.9103$).

The calculated values are then:

Distance	m	3.5	4	4.5	5	5.5	6	6.5	7
Radius (measured)	m	0.27	0.32	0.33	0.41	0.49	0.58	0.61	0.76
Radius (calculated)	m	0.27	0.31	0.35	0.39	0.48	0.57	0.65	0.73

Table 8. Comparison between measured and calculated radius of the mist ring around centreline

Regarding second linear representation of the water mist ring; the imaginary origin of the wider angle (after break up) and the jet centreline is at 2.63 m from the nozzle.
We can now deduce the initial and break up angles in degrees:

$$Initial\ angle = \tan^{-1}\frac{0.39}{5.0} = 4.46°$$

$$Break\ \ up\ angle = \tan^{-1}\frac{0.74}{7.0 - 2.63} = 9.06°$$

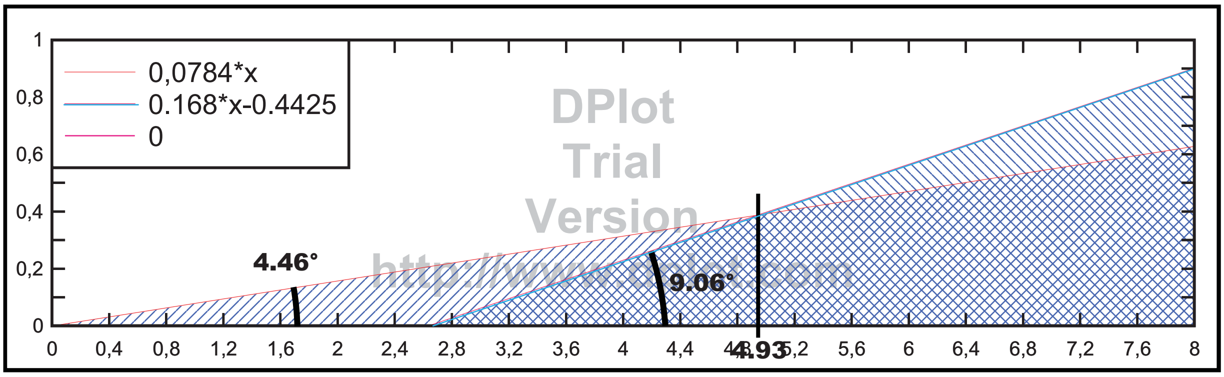


Figure 39 Lengthwise jet geometry, based on linear representation calculations

➔ J. Bjerregaard and D. Olsson (8) found an initial cone angle of 5°, increased to 10° at 5.0 metres from the nozzle. The results obtained by water collecting thanks to the "bottle frame" device seems to be a precise base of water mist measurement sprayed horizontally, since we got an initial angle of 4.5°, and a break up angle of 9.1 at 4.9 m from the mouthpiece.

After verifying the consistency of the results, we can now deduce the flow area in function of distance and the total mass flow rate per unit area, being the basis of calculations of water content in the spray (reminder: Cutting Extinguisher's flow rate = 56 L/min):

Distance	m	3.5	4	4.5	5	5.5	6	6.5	7
Radius (calculated)	m	0.27	0.31	0.35	0.39	0.48	0.57	0.65	0.73
Spray area	m^2	0.24	0.31	0.39	0.48	0.73	1.00	1.33	1.69
Mass flow rate per unit area	$kg/s.\ m^2$	3.95	3.02	2.39	1.93	1.28	0.93	0.70	0.55

Table 9. Spray area in function of distance

Volumetric mist behavioural observations

Thanks to the use of cameras, some interesting empirical findings have been made. These are however only valid in our specific conditions.
The first remark is inspired by looking at these pictures taken at position 1 as mentioned in the chapter referring to video recording (The camera is in the compartment, in the left corner below the nozzle):


At the start of spraying (t = 0)


At t = 0.5 s

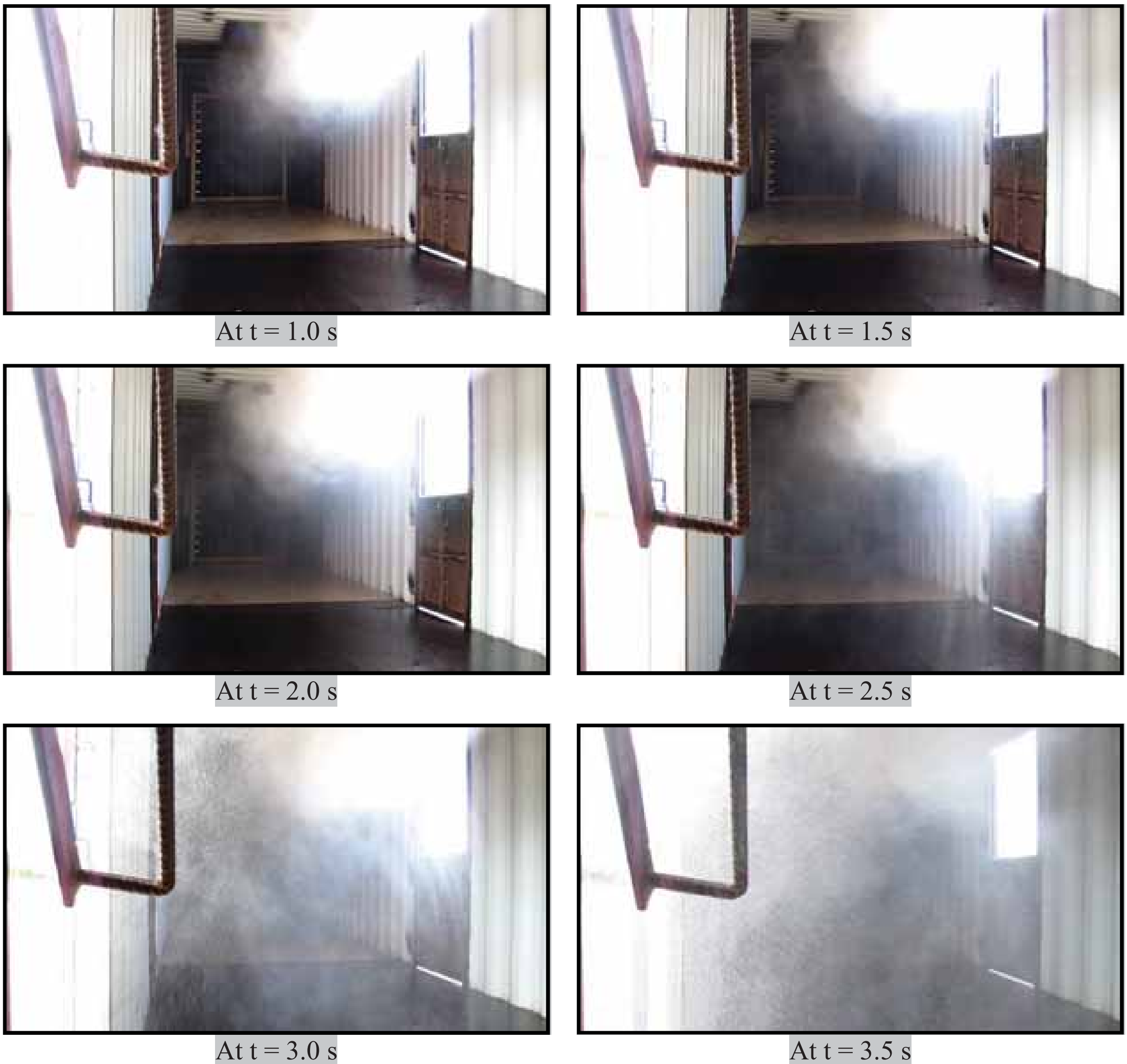


Figure 40 Snapshot pictures taken from a video at intervals of 0.5 s

The records were repeated both with open and closed compartment, but without noticeable difference. Two major things are important to remember from these snapshots:

- First that the entire compartment of 63.7 m^3 is filled by water mist within 3.0 s. This means that the overall average volumetric flow rate of the mist (air and water droplets together) produced by the Cutting Extinguisher reaches values about 21 m^3/s, with a water mass per unit volume of 44 g/m^3, in a 63.7 m^3 compartment at ambient temperature:

Volumetric flow rate of the mist at ambient temperature:

$$\overline{Q_{mist}} = \frac{V_e}{t_{fill}} = \frac{63.70}{3.0} = 21.23\ m^3/s$$

Water content per unit volume:

$$\overline{W_c} = \frac{Q}{Q_{mist}} = \frac{933.3}{21.23} = 43.95\ g/m^3$$

Considering the water mist being pushed and entrained by its velocity and later the resulting air entrainment, we can consider that the mist which is coming back to the front wall was first deflected by the end wall. Since the required time to renew totally the volume of the compartment is 3.0 s, we can deduce the minimum average speed of the mist on lengthwise displacement, which is consequently from at least 7.13 m/s:

$$\overline{v_{mist}} = \frac{2 \times l_c}{t_{fill}} = \frac{21.4}{3.0} = 7.13\ m/s$$

If the actual distance covered by the mist is greater, the velocity is again increased. However, we keep this value as it is the most pessimistic estimation.

- And secondly, that despite a high velocity, generating high droplet momentum, their size seems to be sufficiently small to avoid hitting the glazed window used to protect the camera: the objective remains clear of any impact of drop.

➔ Regarding the snapshots, showing the ability to entirely fill the volume within a very short period of time, and avoiding collision against walls, we can consider the water mist produced by the Cutting Extinguisher as a total flooding agent, behaving in the same manner as extinguishing gases.

From this point, the analysis is based on the statement of a mist expansion behaving as a total flooding agent. Although it does not provide any scientific proof of the fire extinguishing capabilities of the nozzle, let us put in perspective the results obtained with the conventional water requirement to tackle a fire, in order to estimate the extinguishing capabilities of the nozzle in our situation.

Remembering that we consider the water mist as a total flooding agent, and neglect the evaporation and gravity (infinite life time and suspension in the atmosphere); the "horizontal" velocity of the water mist displacement measured by the camera is extended in all directions. It is then possible to estimate the Cutting Extinguisher's surface flow rate, thanks to the average water content per unit volume in the container, and the average mist velocity:

$$Q_s = \overline{W_c} \times \overline{v_{mist}} = 43.95 \times 7.13 = 313.54\ g/m^2.s$$

According to G. Heskestad (The role of water in suppression of fire: a review, Journal of Fire & Flammability, Vol. 11, October 1980, pp 254-262 (11)), the CFR (Critical Flow Rate) required for wood fire is estimated in the worst case measurement at 3.0 $g/m^2.s$

➔ Considering the CFR, we have a surface flow rate 104 times superior than the critical one for wood fire. The conclusions can then be enlarged to the assumption that the Cutting Extinguisher is able to tackle any sort of fire within this enclosure. Providing further reasoning, we can even deduce that the fire will even by extinguished very fast. This is what we will try to estimate in the following section.

Keeping the same assumptions as before, we will now consider the extinguishing requirements on the values of mass per unit volume. The requirements for extinguishing a diffusion flame are comprised into the 140-180 g/m3, increased to 280 g/m^3 for a premixed flame, depending on the work of P. Andersson and G. Holmstedt (3).

If we state that the water is not evaporating, and the required time to flood entirely the compartment being constant at 3.0 s; we can deduce the required time to attain the minimum water content per unit volume, in our compartment:

	Equation	Situation in the compartment at ambient temperature	Lower limit required to extinguish a diffusion flame	Upper limit required to extinguish a diffusion flame	Requirement for a premixed flame
Mass of water per unit volume ($\overline{W_c}$ in g/m^3)	Found in literature	44	140	190	280
Water flow rate (Q in g/s)	$Q = \frac{56}{0.06}$	933	933	933	933
Volumetric flow rate ($\overline{Q_{mist}}$ in m^3/s)	$\overline{Q_{mist}} = \frac{Q}{\overline{W_c}}$	21.23	6.67	4.91	3.33
Flooding/extinguishing time (t_e in s)	$t_e = \frac{V_e}{\overline{Q_{mist}}}$	3	9.56	12.29	19.11

Table 10. Extinguishing time estimations, based on the recommended water content per unit volume, and applied to the concerned compartment and the Cutting Extinguisher characteristics

Taking again the worst case scenario, the maximum required time to extinguish a fire in our compartment is estimated below 20 s. However, the mass per unit volume is not representative of the actual water extinguishing capability, since it is only taking into account the volume action of water. A real situation of compartment fire is influenced for a great part by the oxygen depletion process.
Despite these omissions, and the statements of infinite droplet life time, it is likely to find some extinguishing times of the same order of magnitude. Due to the huge cooling effect, placing the compartment in the "cold" situation within a very short period, and increasing enough the droplets life over the required time to renew the volume by "fresh" mist, thereby causing an increase of the concentration of water per unit volume.
Of course these very fast extinguishing times are still dependant on fire load, area of the openings, and discharged flow rate by the Cutting Extinguisher.

More broadly, these observations show that although a main flow stream following the jet direction dominates, there are some other opposite streams generated in the involved compartment. These are mostly due to pressure effect generated by air entrainment, and it is then likely that the direction of the contra flows is opposite the main one. The "bottle frame" did not measure significant amounts of water travelling in the direction of the jet, but passing somewhere else other than in its cone. That is why even though it would be interesting to reverse the "bottle frame" in order to collect contra flow water; we can already estimate the main flow stream as they appear in the following figure for vertical travel:

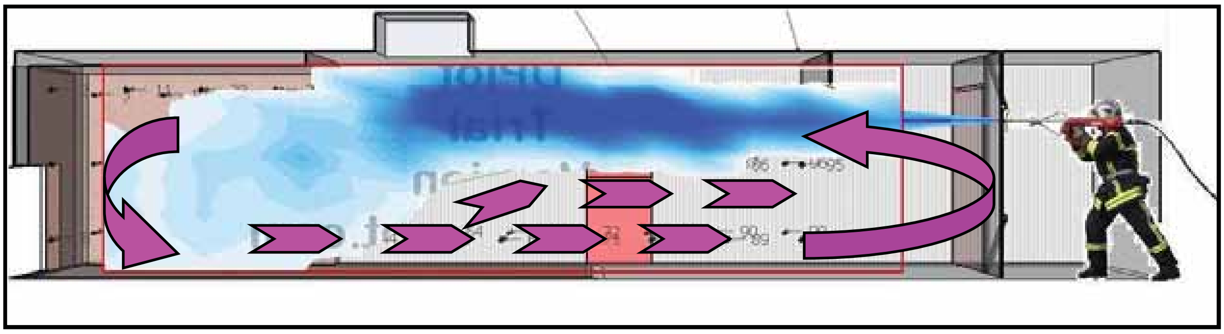


Figure 41. Main mist stream direction in the container, shown on a length-height cross sectional slice. The pink arrows represents the contra flows, travelling in opposite direction, under the main jet, before being re-entrained with the jet, by Venturi effect

Regarding now the horizontal travel, the process is the same, but not as important as on vertical slices, since the jet's direction is exactly in the middle of the left-right distance. It is therefore more probable that the mist has an underlying way of travel, before rising, and reaching the jet entrance point after progressing against the lateral walls.

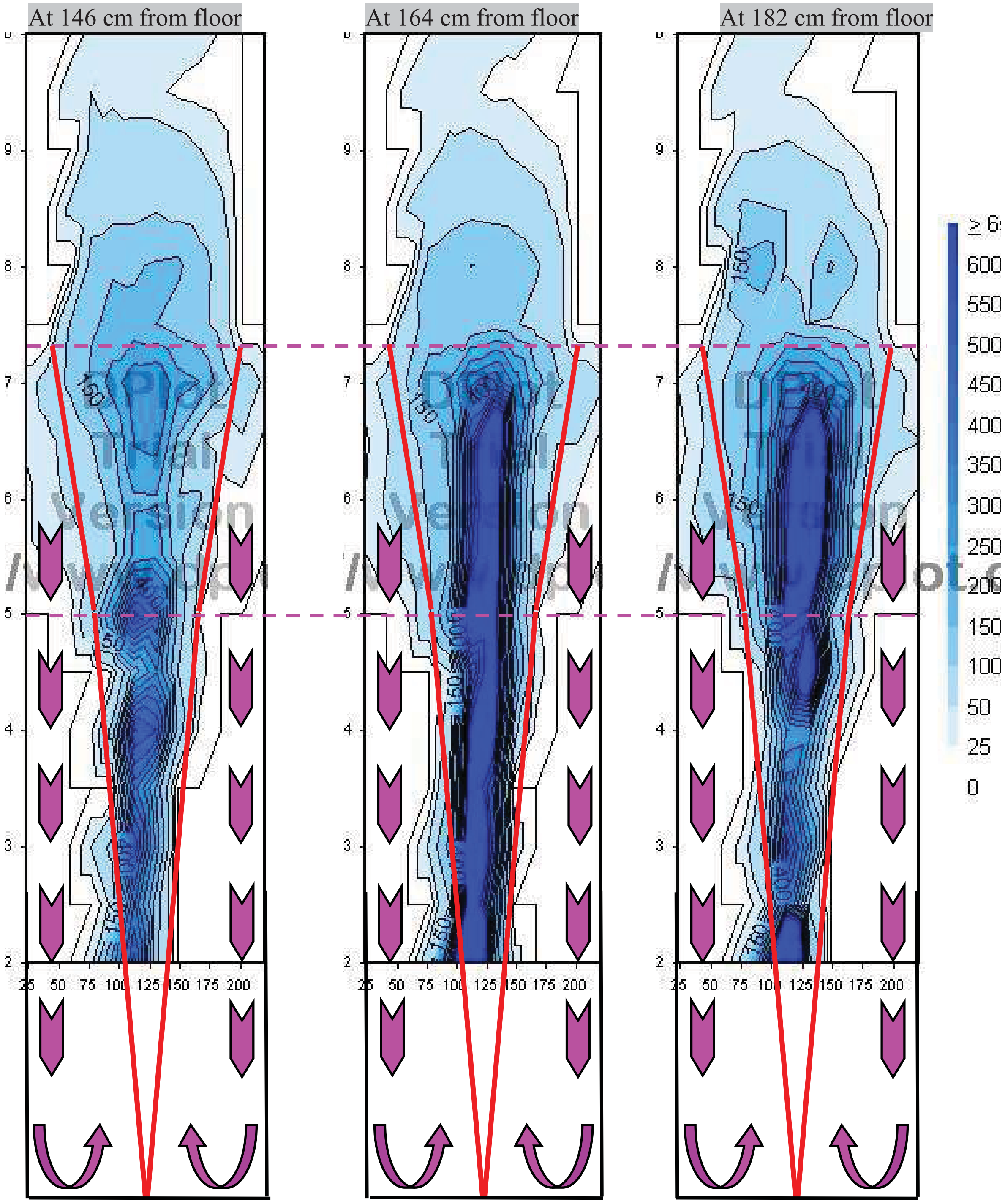


Figure 42. Main mist stream direction in the container, shown on length-width cross sectional slices

The pink arrows represents the contra flows, travelling in opposite direction, emerging mid-way from under the main jet, before being re-entrained with it at the front wall, by Venturi effect

Fire suppression capabilities of water mist

In order to assess the fire suppression capabilities of the Cutting Extinguisher, following the experimental protocol described above, we planned to carry out at least 9 burnings, corresponding to 8 different scenarios. The scenarios were defined by the studied parameters (Influence of the burning surface (S_f), influence of the openings (A_o), and influence of the water flow rate (Q)), which gave fire extinguishing in the following conditions:

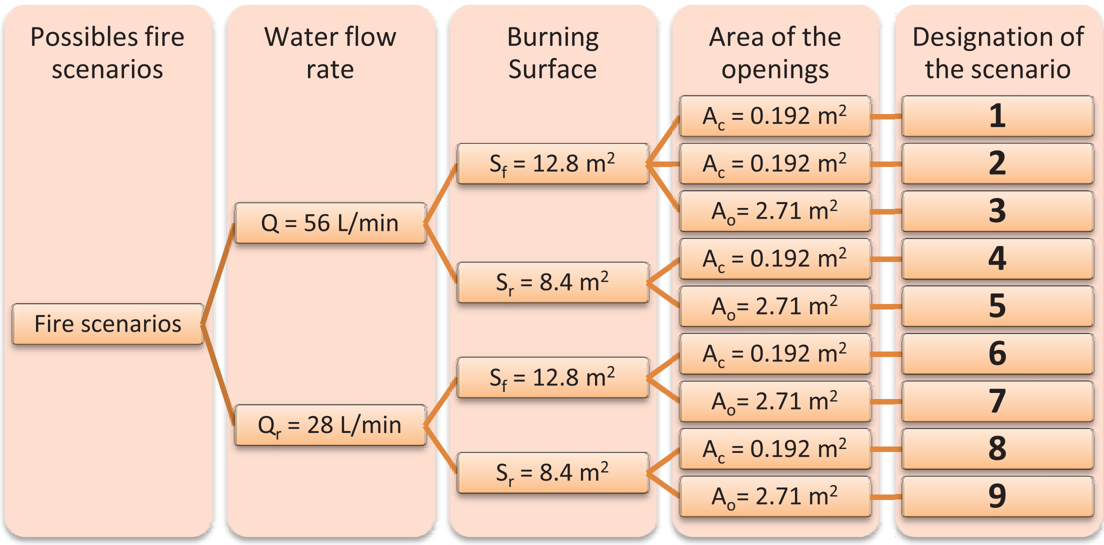


Table 11. Studied parameter tree, leading to the definition of the Scenarios

However, due to several issues, it was not possible to carry out all the experiments, especially due to the constraint on time allowed to run them and gather all the necessary factors, fire fighters and staff to ensure safety. Moreover, since the compartment was brand new, it required a sort of "pre-burn" in order to consume all the painting and heat properly all the steel structure at least one time before full instrumentation. That is why the number of possible tests was reduced to 6, but also to let the compartment cool down, and evacuate moisture.

Unfortunately, there is always some risk of apparatus break down when doing real experiments. This was the case with the data recording software, which stopped responding twice. On one of these burnings, we lost the signal just before extinguishing, and on the second, it happened after 1 minute extinguishing, which was still enough time to exploit the data.

So we will base our analysis on 5 successful tests, which were corresponding to the scenarios **1**, **2**, **3**, **4** and **6**. Please note also that the scenarios **1** and **2** are identical, the number **2** used as a control for repeatability

All the fire scenarios followed the experimental protocol detailed above.

Since the assessment concerns the compartment fires, sometimes without openings, we could not check the extinguishing times, meaning in that sense the delay to achieve the tackling of flaming part of combustion. Furthermore, it is very unlikely to find some flames in a compartment which has no fresh air input; which creates un-burnt gases production, and leads to dangerous Smoke Gases Explosion situations (SGE). That is why most of our data analysis is based on the evolution of temperatures. However, the **Appendice A3** gives some indices on the average flame extinguishing time based on video record of the scenario 3 (with openings, providing the continuity of flaming combustion and brightness for recording), although that represents only one scenario.

Thanks to temperature recording, we could draw the fire curves of the scenarios, in function of time evolution. The thermocouple used for this is the TC 2, located at 0.4 m from the bottom wall, midway of the width and at 2.0 height of the compartment.

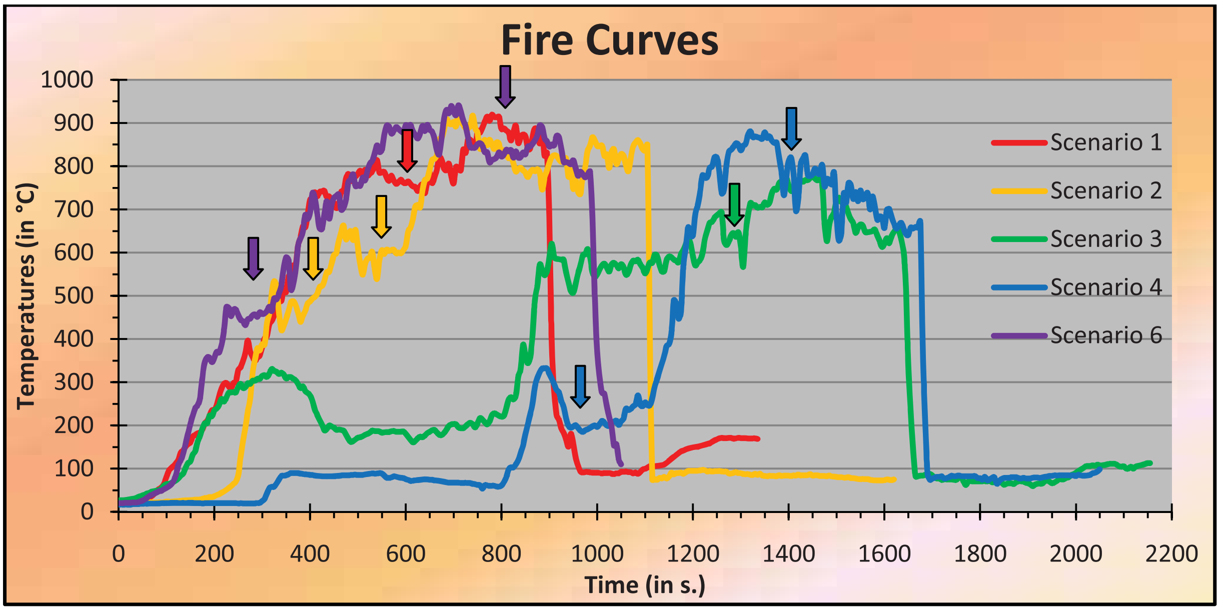


Figure 43. Temperature evolution during all the recording session, for each scenario carried out

Remaining very general, we can still mention some of the more obvious remarks concerning the fire development, visible on the curves.
The quasi vertical fall of the temperatures are due to the introduction of water mist in the compartment, followed by three minutes of continuous spraying, whereas the early small drops shown by the arrows are caused by the manipulation of the smoke vent, by the fire fighter responsible for the burning.
The growing parts of the fires are very similar in Scenarios 1, 2 and 6… which also corresponds to experiments with the same fire parameters (Same Fuel load, and same area of openings). Lowering the quantity of combustible (Scenario 4) or maintaining constant wide opening (Scenario 3) had, as a consequence, fire which had great difficulty establishing itself and reach the fully developed stage. That is why they are much later, with regard to the start of the data logging time.

Temperature records

Because of the number of thermocouples installed, and their particular repartition in a defined mesh of 0.8 m a side, 50.69 m^3 over the whole volume of 63.7 m^3 of the compartment providing continuous scanning, during all the burning, extinguishing phase, and waiting time of 3 minutes; the most attention will be paid to their analysis. For the very first time, we propose to study the required time to achieve significant temperature drops at several positions in the compartment.

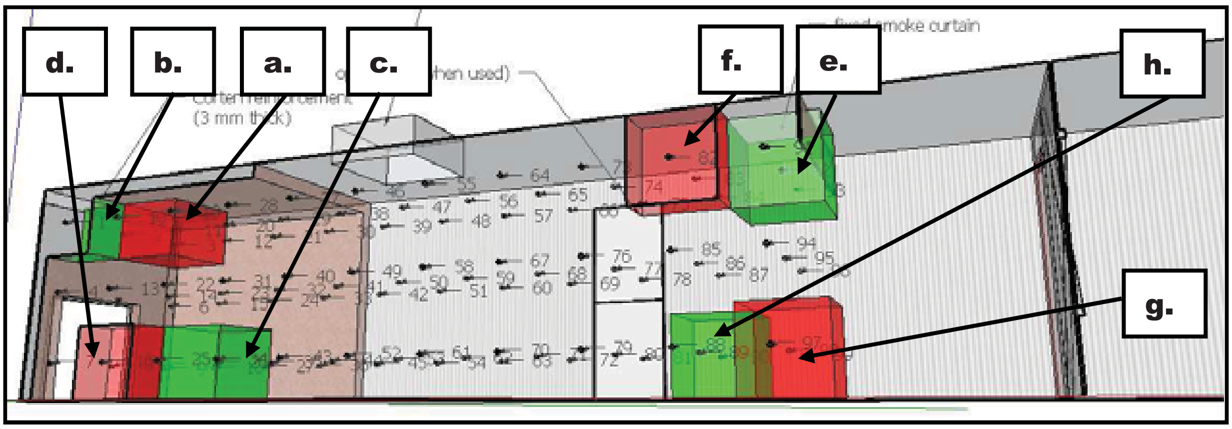
Heat extraction by temperature cooling

Since it was not possible to have a visual control on the flame blowing, we base our assessment on the extinguishing capabilities of the water mist on the temperature decrease. Keeping in mind that there is no fire identical to another, the best way to define extinguishing is not to focus on the time required to drop below a temperature limit, but to define a minimum temperature drop, regardless of the value at the start of extinguishing. For our trials, we propose to have a look at the time required to reach a drop of 100°C,,until we reach the lower final level of 100°C, which is the lowest temperature for water vaporization.
As the main issue is to measure the capability of global cooling in the compartment, we have to take three factors into account:

- The location of the fire, which is in the 2.5 m of the end of the compartment, generates variations in the length of the compartment.
- The smoke stratification, generating smooth temperature repartition, from hotter layer on the ceiling, to colder on the floor (on the height of the compartment)
- The water mist spray pattern, and especially its inner core, progressing in the container through its central axis, regarding the width.

Moreover, from the conclusions of the water mist behaviour in cold situation, showing a global filling of the compartment, we have the opportunity here to see in which proportions it compares in a fire situation, and, apposingly, what sort of contrasts that can be noticed. So in order to make this operation feasible, and outline the cooling effect, regardless of the location variations, we analyse all the representative locations, including all possible variations with the three factors (three dimensions). Thus with the three factors, having each two possible answers, we have a total of 8 positions which are of interest, and are represented by a thermocouple (See **Appendice A1** for exact location)

a.	Fire zone + smoke layer + jet centreline	TC 11
b.	Fire zone + smoke layer + ~~jet centreline~~	TC 01
c.	Fire zone + ~~smoke layer~~ + jet centreline	TC 26
d.	Fire zone + ~~smoke layer~~ + ~~jet centreline~~	TC 16
e.	~~Fire zone~~ + smoke layer + jet centreline	TC 92
f.	~~Fire zone~~ + smoke layer + ~~jet centreline~~	TC 82
g.	~~Fire zone~~ + ~~smoke layer~~ + jet centreline	TC 98
h.	~~Fire zone~~ + ~~smoke layer~~ + ~~jet centreline~~	TC 90



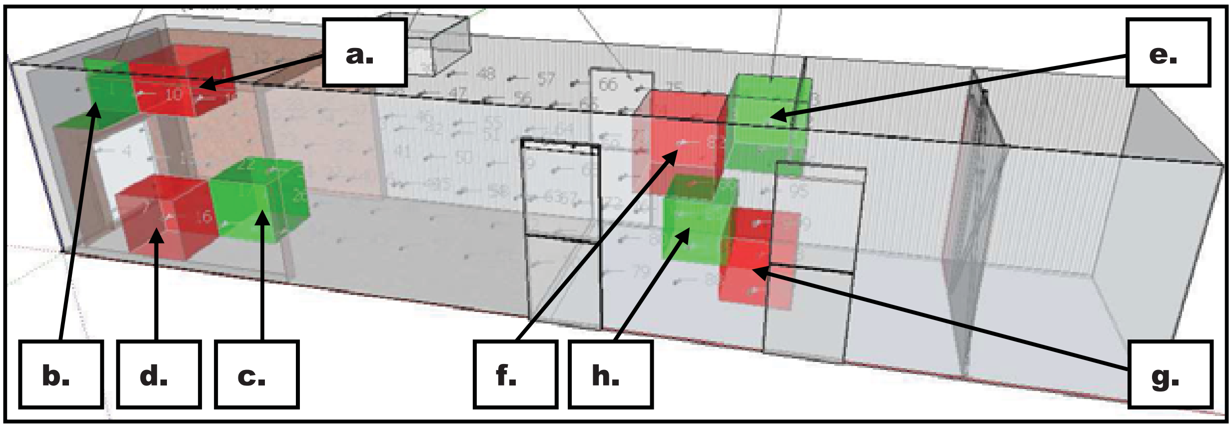
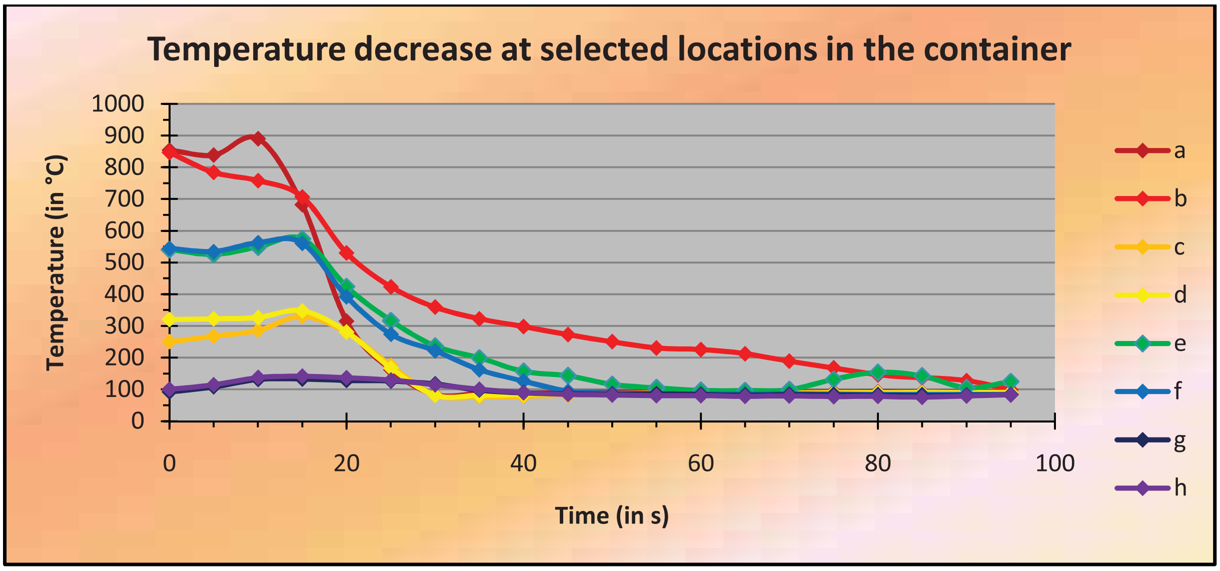


Figure 44. Position of the control thermocouples, and their control volume associated. Remember that the fire zone is visible since it has a CorTen dubbing, in brown

Then, based on the time of start of extinguishing of each fire scenario and the temperature drops, we can establish the following table (Remembering that we have a scanning interval of 5 s between each data record, the time steps given are pessimistic; i.e. if there is there is a temperature drop of 173 °C within 5 s and 305 °C within 10 s, we take 5 s for a drop of 100°C, and 10 s for a drop of 300 °C, the 200°C drop step is marked as "/". And so on...)
NB: the hatched boxes disable the possibility of higher temperature drop than from their initial value, until the limit of 100°C.

The analysis will focus on a first part only on the differences within one defined scenario, with no comparison between the different burnings. This part will then try to outline until a certain point "how the mist behaves" in the compartment

- **Scenario 1: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2).**



Scenario 1 ($Q + S_f + A_c$)		Times are in s							
Position		a.	b.	c.	d.	e.	f.	g.	h.
Last T° record before extinguishing (at 885 s)		854	847	250	320	541	544	92	100
Time required to have	100 °C drop	15	15	/	25	20	15		
	200 °C drop	/	/		/	25	25		
	300 °C drop	/	20			30	30		
	400 °C drop	/	25			50	40		
	500 °C drop	20	35						
	600 °C drop	25	55						
	700 °C drop	/	85						
Total time to go below 100°C		30	95	30	30	60	45		

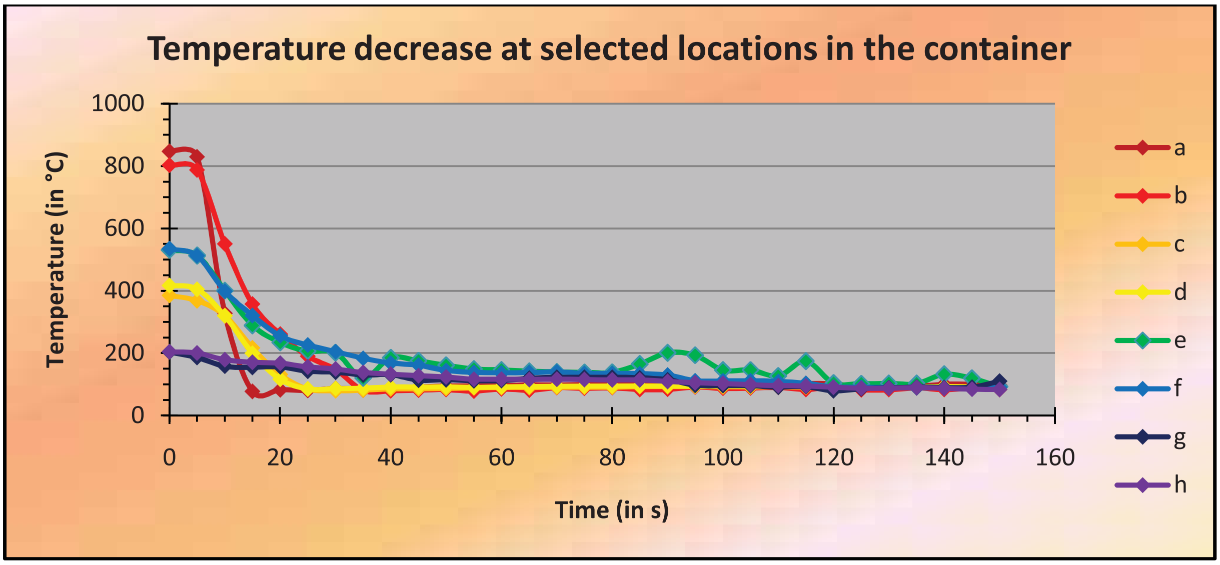
Table 12. Temperature evolution during extinguishment, at several positions in the container, and consequent times to drop in steps of 100°C with the fire scenario n°1

The temperature in the upper part of the fire area is very hot at the start of extinguishing, as positions a. and b. are showing around 850°C. We can see a sort of plateau during the 10 first seconds; the time for water mist to "dig its hole" in the smoke layer. The initial drop of a 100°C step happens first in the axis of the jet (a., b. and f.) after 15 seconds. 5 seconds later, it is also the case for the rest of the volume. We can imagine here the water mist spray cooling the immediate area of penetration first, and pushing the smoke layer in the fire area, before expanding to the entire volume. This hypothesis could sustain the small bumps occurring at 10 seconds in the fire zone which is directly targeted, and is visible 5 seconds later for the other positions.

There is no visible mixing of the gases, which would be highlighted by uniform temperature over the entire compartment. However, even if it is not the case, the decrease is still quite balanced on every position, excepting b. since all the locations are transmitting a time comprised between 30 and 60 seconds to pass below 100°C. This phenomenon is logical, since the parts of volume at higher temperature have a greater delta with the water droplet temperature, causing a faster temperature decrease (visible on the graph by a steeper slope)

- The mean temperature measured by 97 TC at the start of extinguishing is 436.5 °C
- After 30 seconds of spraying, we measure a mean temperature of 138 °C, which corresponds to 28 kg of water used
- After 40 seconds of spraying, the mean temperature has dropped down to 100 °C, requiring 37 kg of water.

➢ **<u>Scenario 2: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2).</u>**



Scenario 2 ($Q + S_f + A_c$)		Times are in s							
Position		a.	b.	c.	d.	e.	f.	g.	h.
Last T° record before extinguishing (at 1100 s)		848	803	385	417	531	535	203	205
Time required to have	100 °C drop	/	/	15	/	10	10	/	100
	200 °C drop	10	10	20	15	15	15		
	300 °C drop	/	/		20	25	25		
	400 °C drop	/	20			110	75		
	500 °C drop	15	25						
	600 °C drop	/	30						
	700 °C drop	/	/						
Total time to go below 100°C		20	40	25	25	150	125	95	105

Table 13. Temperature evolution during extinguishment, at several positions in the container, and consequent times to drop in steps of 100°C with the fire scenario n°2

The second scenario shows again a very hot upper layer in the fire area, but this time also some floor layers getting strongly heated, as confirms the positions g. and h. The plateau is shorter, only 5 seconds, before some very important temperature falls; in 20 seconds all the positions are transmitting values below 300 °C, and below 200 °C everywhere in 30 seconds.

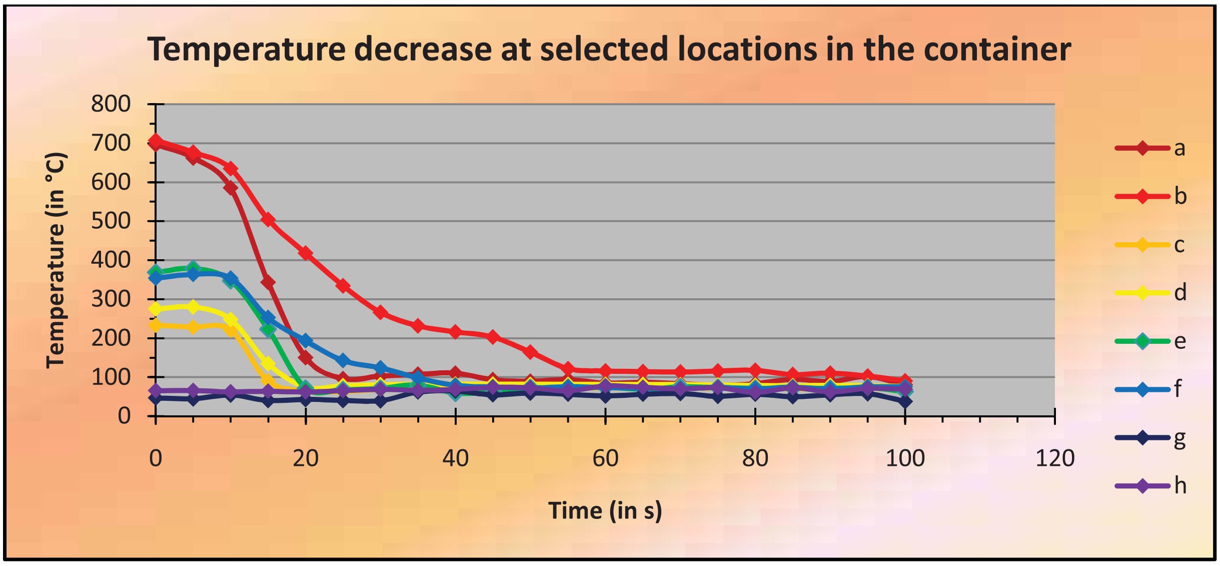
The second period however, takes a much longer time; all the volume seems to be remaining at 130-150 °C during a long period (At least until 100 seconds, according to the graph, if we neglect the bumps at position e.), measured at 150 seconds for e.

Moreover, something blatant on this scenario (also present in scenario 1, but less marked), the smoke layer in the opposite part of the fire area (close to the wall where the jet is coming out) takes the longest to cool down (position e. and f.): after 25 seconds all the positions are indicating temperature below 200 °C except on those two location. Concerning the differences between them, we can observe the position in the centreline of the jet dropping faster than at closer position of the boundaries. From all these factors, we do not tend to think it is because of a slower mist expansion, which would appear illogical, since the conditions were the same than in scenario 1, but rather on a difference on heating time of the boundaries, which could be responsible for the delay in reducing the temperature. This point will be clarified in a later part, in **Appendice A4**.

- The mean temperature measured by 97 TC at the start of extinguishing is 496 °C

- After 30 seconds of spraying, we measure a mean temperature of 142 °C, which corresponds to 28 kg of water used
- After 90 seconds of spraying, the mean temperature has dropped down to 100 °C, requiring 84 kg of water.

➢ **Scenario 3: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and with openings (2.71 m^2).**



Scenario 3 ($Q + S_f + A_o$)		Times are in s							
Position		a.	b.	c.	d.	e.	f.	g.	h.
Last T° record before extinguishing (at 1635 s)		697	707	233	275	369	354	47	66
Time required to have	100 °C drop	10	/	/	15	15	15		
	200 °C drop	/	15			/	25		
	300 °C drop	15	25						
	400 °C drop	/	30						
	500 °C drop	20	45						
	600 °C drop		85						
	700 °C drop								
Total time to go below 100°C		45	100	15	20	20	30		

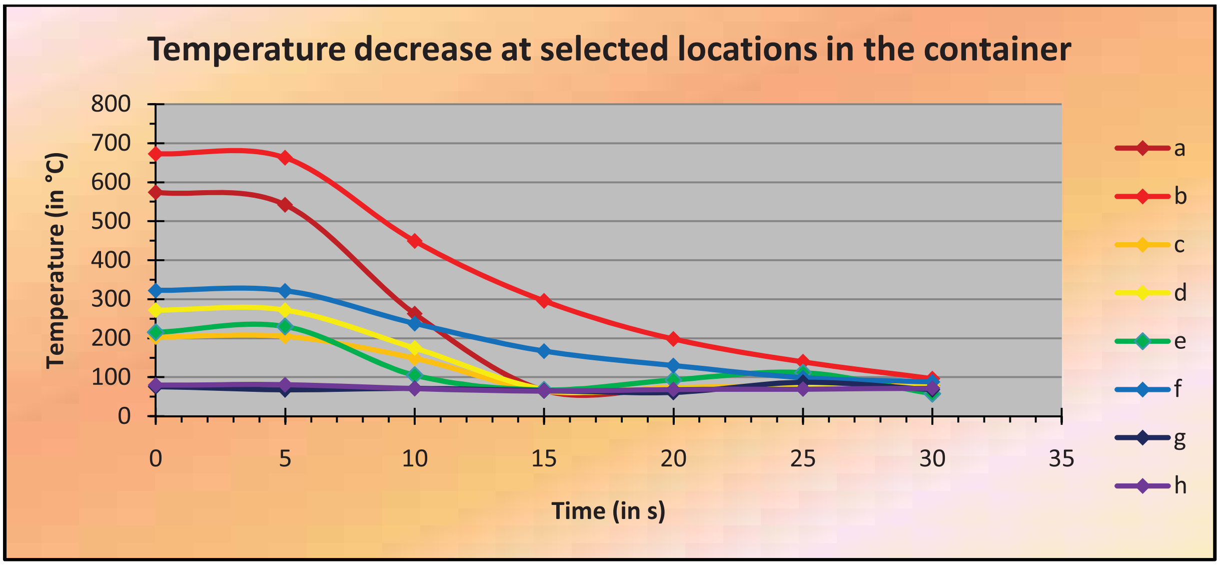
Table 14. Temperature evolution during extinguishment, at several positions in the container, and consequent times to drop from steps of 100°C with the fire scenario n°3

At first sight, we immediately notice that the initial temperatures are not as high as in the two previous scenarios. Indeed, the floor temperatures do not even reach 70 °C.
Regarding the temperature decrease, there is a fast overall drop, except on position b., which shows quite a low slope. All the points are below 100 °C within 45 seconds, reduced to 20 seconds for positions c. and d., which are in the lower part of the compartment. Since this scenario was done with openings, this very low layer of temperatures near to the floor could be explained by a phenomenon of air entrainment during extinguishing, via the lower part of the openings.

- The mean temperature measured by 86 TC at the start of extinguishing is 294 °C
- After 20 seconds of spraying, we measure a mean temperature of 107 °C, which corresponds to 19 kg of water used
- After 30 seconds of spraying, the mean temperature has dropped down to 90 °C, requiring 28 kg of water.

Note: even if the mean is quite representative of the volume, it is important to note that this scenario was the last to be undertaken, and most of the TC break downs were located in the fire area, which could reduce the mean value more than the real situation.

- **Scenario 4: Cutting Extinguisher at normal flow rate (56 L/min), reduced combustible load (8.4 m^2) and no openings (0.192 m^2).**



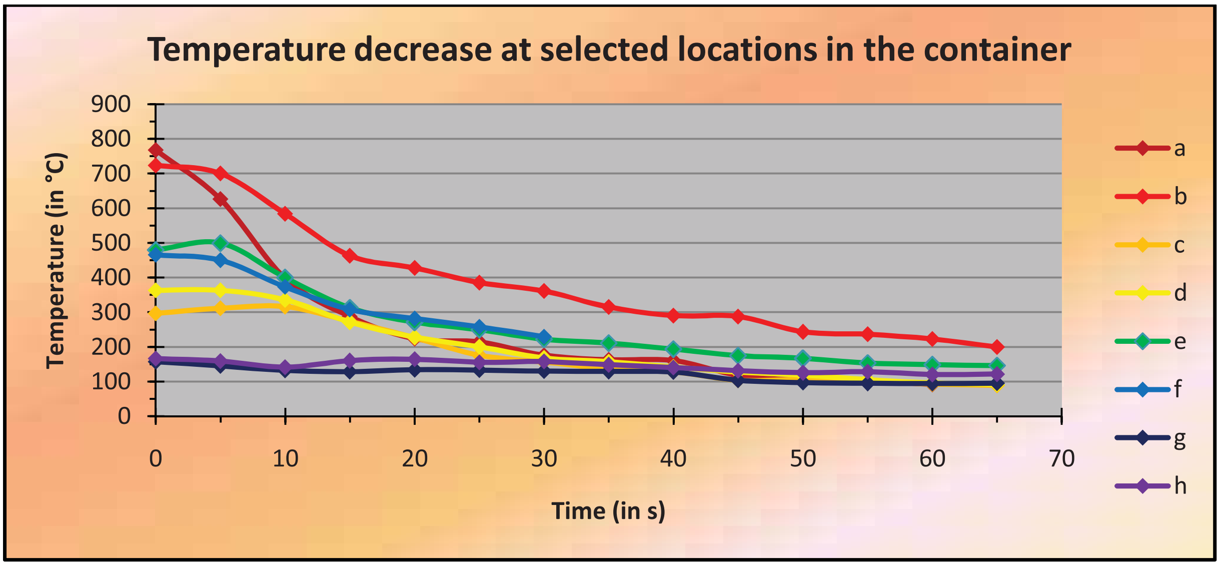
Scenario 4 ($Q + S_r + A_c$)		Times are in s							
Position		a.	b.	c.	d.	e.	f.	g.	h.
Last T° record before extinguishing (at 1670 s)		574	673	203	272	216	322	76	80
Time required to have	100 °C drop	/	/	/	/	10	15		
	200 °C drop	/	10				/		
	300 °C drop	10	15						
	400 °C drop	/	20						
	500 °C drop		25						
	600 °C drop								
	700 °C drop								
Total time to go below 100°C		15	30	15	15	15	25		

Table 15. Temperature evolution during extinguishment, at several positions in the container, and consequent times to drop from steps of 100°C with the fire scenario n°4

Scenario 4 shows a strange phenomenon: all the pairs of positions of same height and depth, but either in the centreline or closer to a wall show a significant difference, which was not the case in the previous scenarios. For example, a. and b. have 100 °C difference, as well as e. and f. and even c. and d. This cannot be precisely explained on graphical single position measurements, so we will consider these astonishing results later thanks to another way of presenting data, in **Appendice A5**.
Concerning the gas cooling process, we can outline very fast temperature drops, shown by steep and continuous slopes on the graph; by the way, all the points are below 100 °C within 30 seconds. This is not very surprising, since the locations which are usually the hottest are only at 670 °C before extinguishing.
Again, like on scenario 2, the plateau is only lasting 5 seconds, before an overall temperature decrease. There is no noticeable difference between the front and the end positions, which could suggest a fastest water mist flooding in the present situation (no delay between fire area, and opposite zone, with regards to the temperature drops)

- The mean temperature measured by 94 TC at the start of extinguishing is 265 °C
- After 15 seconds of spraying, we measure a mean temperature of 102 °C, which corresponds to 14 kg of water used
- After 30 seconds of spraying, the mean temperature has dropped down to 82 °C, requiring 28 kg of water.

➢ **Scenario 6: Cutting Extinguisher at reduced flow rate (28 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)**



Scenario 6 ($Q_r + S_f + A_c$)		Times are in s							
Position		a.	b.	c.	d.	e.	f.	g.	h.
Last T° record before extinguishing (at 985 s)		768	723	297	364	480	466	157	167
Time required to have	100 °C drop	5	10	25	25	15	15		
	200 °C drop	/	15		40	20	25		
	300 °C drop	10	25			45	55		
	400 °C drop	15	35						
	500 °C drop	20	60						
	600 °C drop	35	X						
	700 °C drop								
Total time to go below 100°C		60	X	60	65	X	X	50	X

Table 16. Temperature evolution during extinguishment, at several positions in the container, and consequent times to drop from steps of 100°C with the fire scenario n°6

Again, this scenario is the same as scenario 1 and 2, regarding the fire growth, and again, we have quite high temperatures, up to 770 °C at position a. the plateau of 5 seconds is noticeable here also. The cooling phase however, is quite interesting: if the position a. is subjected to its first 100°C drop within 5 seconds, it is lasting much longer for the rest of the volume, and especially for the end layer, represented by c. and d. which require 25 seconds before getting their first step drop. We are in a situation where the Cutting Extinguisher only provides a flow rate of 28 L/min, which could explain the difficulty to "fill" the entire volume as fast as in the other cases, even if it is sufficient to tackle the smoke which is just in the centreline of the jet. This is also why the slopes are so weak: we are only below 200 °C after 65 seconds. Unfortunately, we cannot study the time to descend until 100 °C because of a crash of the acquisition software after these 65 seconds (Missing data are shown as white crosses on red background).

- The mean temperature measured by 96 TC at the start of extinguishing is 417 °C
- After 30 seconds of spraying, we measure a mean temperature of 183 °C, which corresponds to 14 kg of water used
- After 65 seconds (last measured data) of spraying, the mean temperature has dropped down to 116 °C, requiring 30 kg of water.

➔ Regardless of the scenario, we can still make conclusions on some general behaviour of the temperatures regarding their location. Position b. is, irrespective of the situation, the hardest to cool down to the 100 °C limit temperature. It is then the worst case position, regarding the ability to cool the hot gases, and being reached by the water mist, which correspond to the addition of the three factors combined in that order: "Fire zone + smoke layer + ~~jet centreline~~". However, all positions are still under 200°C after less than 70 seconds. We also can mention as a general rule, the presence of a sort of "plateau" during the 5 to 10 first seconds of extinguishing, very likely to be caused by the time required to "dig a passage" into the smoke layer, where the jet is targeting, before expansion occurs.

Without confusing the earlier mentioned hardest position to cool down to 100 °C; there is another position which has difficulties in the initial drop of 100 °C, regardless to the temperature at the start of extinguishing. This is the area near to the floor, in the fire zone (position c. and d.), possibly because of a phenomenon of air cushion caused by the pressure exerted by the thrust of the jet and the entrained air masses on the dead end, which prevents the water mist properly reaching the corners of the compartment at the early stage. The smoke cushion being progressively cooled down, the currents can start to mix them in the volume, and finish by cooling all the structure.

Finally, considering the amount of water sprayed into the container, we can see that in all scenarios, 30 kg is largely sufficient to cause a drop of the overall mean temperature below 150 °C, which is more than enough to tackle a fire, and cool the smoke gases to be safe enough for a fire fighting BA Team to penetrate in the structure and finish flooding the remaining charring products. Distributed over the entire volume of the container, the amount of water per unit volume is lower than 471 g per cubic metre. ($\frac{Water\ mass}{V_e} = \frac{30\times10^3}{63.7} = 470.9\ g/m^3$)

➔ Taking account of the scenarios and comparing them with each other begins to illuminate our knowledge on the influence of the studied parameters. Let us start with Scenario 3, having openings; as a first remark we notice that the temperature was at least 150 °C lower than in the scenarios without openings. The reason for that is due mainly because of the ability of smoke to evacuate the compartment within a short period of time, instead of remaining in it, heating the boundaries, and generating a sort of "pressure cooker effect". Even if the compartment, depending on how it is managed by the fire fighter responsible for this, is opened during fire growth, the few minutes delay between closing, and start of extinguishing is sufficient for the compartment to be subjected to that phenomenon.

By deduction, lower temperatures mean

Figure 45. Thickness of the smoke layer at the fully developed stage of fire, for scenario 3

easier extinguishing, so the fear of lower inerting effect by oxygen depletion, in not an inconvenience, since it is balanced by the advantage of a lower average temperature, which is at least applicable to volumes up to 60 m^3, and which has an opening area of at least an open window and door. Moreover, the so called "inerting effect" is not having a real influence on the gas tightness, as we will see later, since there is no volume expansion, but rather volume decrease, due to under pressure...

Scenario 4 is focusing on the influence of the combustible fuel. As the difference between the scenarios with full fuel load (8.4 instead of 12.8 m^2), having a reduced burning area means having a lower overall average area, and then again a facilitated extinguishing phase. So, it is clear that the combustible fuel has an influence in extinguishing: the heavier the fuel load in the compartment, the slower the extinguishing is. But even with a large fuel load, the Cutting Extinguisher tackles and cools down the fire without any major obstacle, since we are speaking here about differences of a few tens of seconds, which is negligible compared with the time scale of a fire extinguished by a fire brigade, or even by fixed water mist sprinklers.

And, the last parameter of influence, and maybe the one showing the most important variations with all the others, is the difference of flow rate. Contrary to the two other parameters which are not possible to vary or modify, the flow rate is a characteristic of the Cutting Extinguisher. The Scenario 6 is the subject of an extinguishing jet with a 28 L/min nozzle instead of 56 L/min, and it appears immediately that the gas phase cooling is slower. Again, it does not mean extinguishing is getting impossible, but the required time is longer. Another interesting point, we could see that the temperature decrease was particularly difficult in the top left corner of the fire area, encouraging us to think that a smaller flow rate would cause a problem in complex shaped compartments. Because of a smaller volume of air indrawn, smaller air streams are generated, and therefore more difficulty is experienced, distributing water mist to the entire compartment. However, keeping in mind that the normally used flow rate is 56 L/min, with a flow rate reduction only in the case of a pump or engine break down, we can consider that the majority of the fires are treated with higher flow rate, which provide better extinguishing effect.

As noticed in an earlier summary, the worst case position for measuring temperature decrease is position b., in the top left corner of the fire area. In order to confirm our statements, and looking at some other way of comparing the scenarios, we select them all in a second stage, showing the temperature evolution of all the scenarios, on the same location:

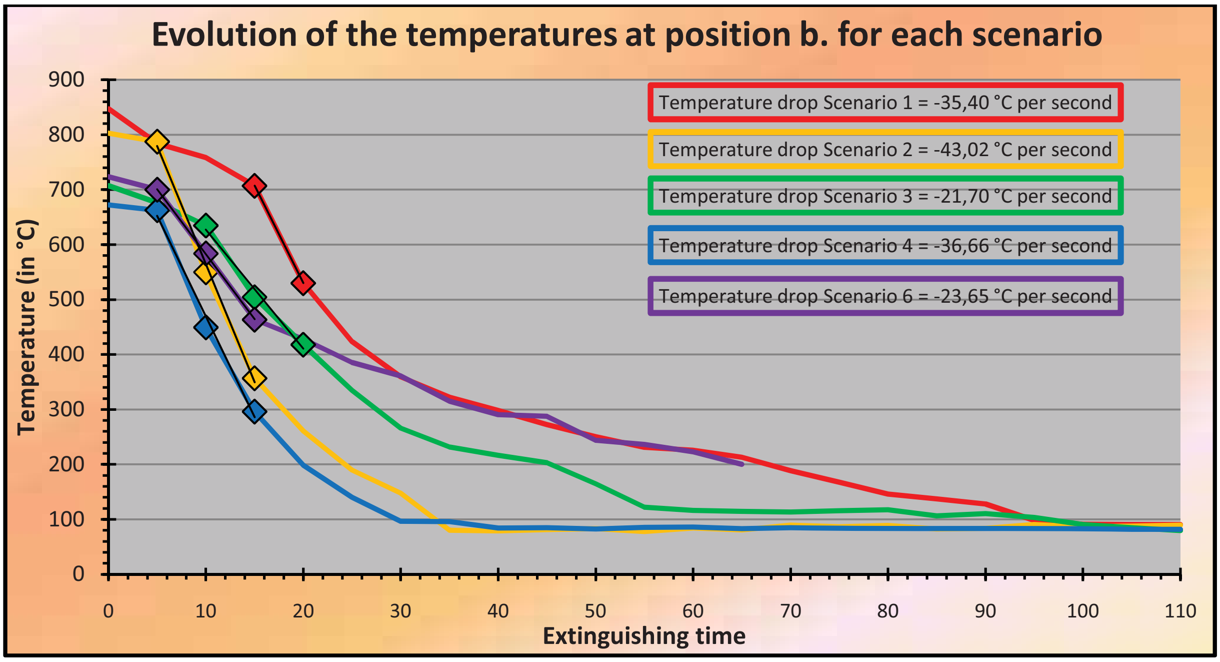
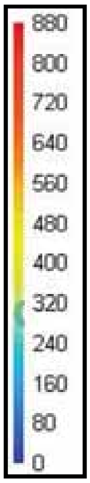


Figure 46. Analysis of the temperature drop at their steeper slope for each fire scenario, and their corresponding equation in function of time

A rough analysis of the curves would make us think of a complete lack of credibility concerning the repeatability of the burnings. However, the choice of a single position is not a safe way of measuring repeatability, and looking at the time to slip below the limit of 100°C is also wrong, since the start temperatures were not the same. But it is possible, to observe the steepest part of the slopes. They occur between 5 to 15 seconds after the start of extinguishing, up to 20 seconds of spraying. By calculating their linear curve equation, we can obtain a value which corresponds to the temperature loss per second, at this stage of the steeper slope.
From this we can see that the fastest temperature cooling scenario is the n°2, which means with the Cutting Extinguisher's normal flow rate, high fuel load, and no openings in the compartment. The values found are up to 43 °C loss per second.
In the same range of 35 °C loss per second, we find the second scenario, which has the same parameters, and the scenario 4, which differentiate it by a smaller fuel burning area. The slowest temperature decrease are "only" having values of 22-24 °C loss per second, and are either due to the presence of openings, or to a lower water flow rate.
Thus, the conclusions that we draw rather seem to confirm most of them, except by the influence of the openings, where it seems finally to still increase the difficulty of cooling ability, regarding to this position. Nevertheless, by calculating the time to fall under a reasonable temperature; either with higher temperatures at the start, and high cooling velocity, or lower start temperature and a lower cooling velocity; we get a final result which is exactly the same. So, yes having openings seems to hinder the cooling, but no, the final extinguishing does not consequently last longer, since it is balanced by lower temperatures.

Volumetric flooding properties

Thanks to the cold flux measurements, and the information given in literature, we are quite sure that the water mist has good volume expanding and filling properties, in the entire shape of the structure where it is sprayed. The question now asked is to what extent is it also the case in a room involved by fire. We know that the combustion needs indrawn air to be sustained, as well as a smoke outcome. In terms of the height of a room, there is a progressive temperature repartition, from hottest part just beneath the ceiling, to the coolest at floor level. This temperature distribution is due to the properties of gases to expand when they are subjected to heat. For a same remaining volume, they are then lighter, and tend to elevate, whereas heavier cold air is crawling on the lower layers. The phenomenon of gas elevation is also a heat transfer process, named convection. And the flows generated by these hot gases can be called convection flows.



In a compartment, the horizontal direction of these flows generates from the fire, to the colder parts of the room, and if it is sealed, the process slows down until all the oxygen is consumed and the heat generation from the fire gradually "dries up".

When we carried out our experiments, the compartment was either closed for a period of time before extinguishing, or remained open. Since the Cutting Extinguisher was oriented from the front wall to the fire area, and located quite high (1.65 m) it had to counter this stratified flow of smoke and combustion gases. In those conditions it is then unrealistic to hope the water mist behaves the same way as in a clear atmosphere.

We propose to analyse and try to answer this question in more detail than was possible with only graphs. Thus, we will use planar representation of the temperature through the compartment during extinguishing. The slices are vertical cross sectional views taken in the length of the compartment, exactly in the centreline of the width, and on the route of the water jet.

- **<u>Scenario 1: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)</u>**

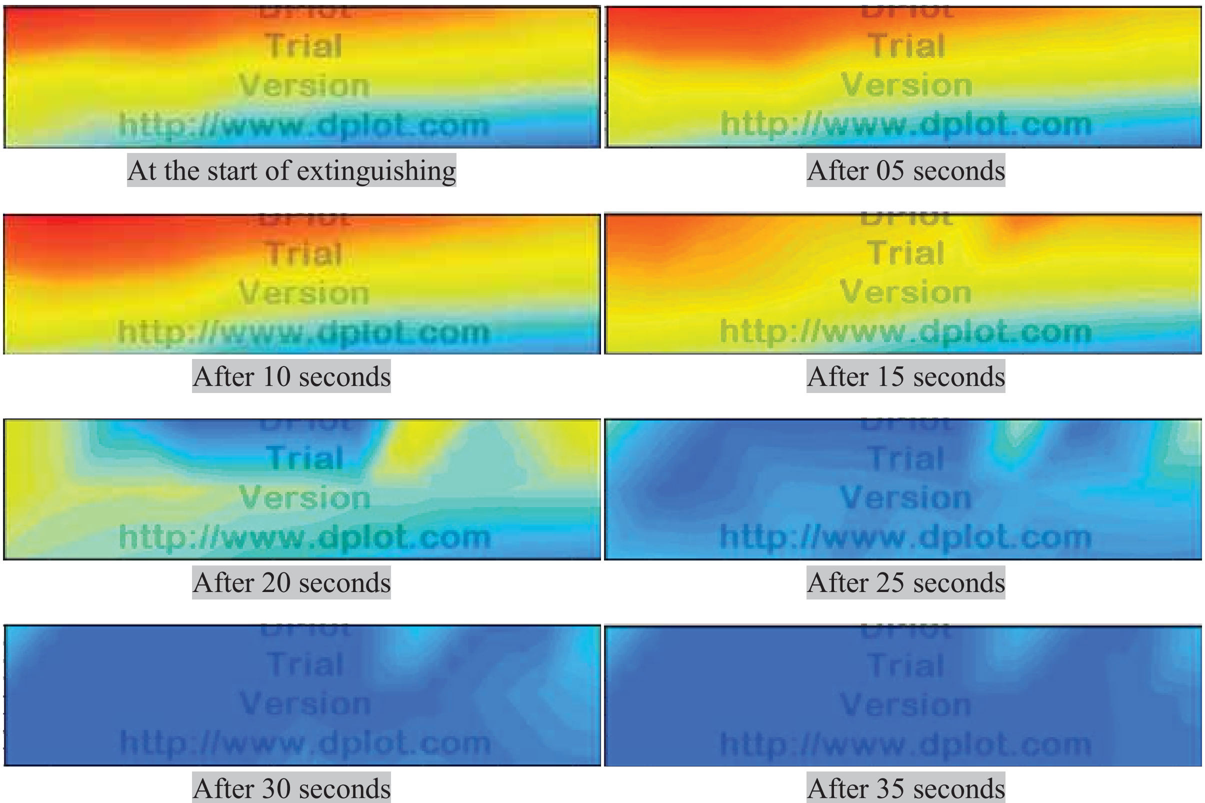


Figure 47. Evolution of the temperatures on lengthwise slice of the container, during extinguishment, for scenario 1

The entire smoke layer is very hot and likely to get involved in flame if there is sufficient oxygen. The red areas show temperature exceeding 800 °C.

As predicable, nothing seems to happen during the 10 first seconds, except a tiny lowering of the temperature layer. At 15 seconds, the extinguishing is in full swing, and all the room has dropped down to temperatures of 500 °C. Please also note that the penetration of the water jet did not engulf the cool area on the floor. 5 seconds later, the compartment continues to cool, and the “blue area” is gradually gaining ground. There are only some few pockets remaining at 400 °C in the fire area and beside the curtain, but all the rest of the volume is below 200 °C.
After only 35 seconds, the container is “blue” everywhere, meaning by this colour that we are about 100 °C.

- **<u>Scenario 2: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)</u>**

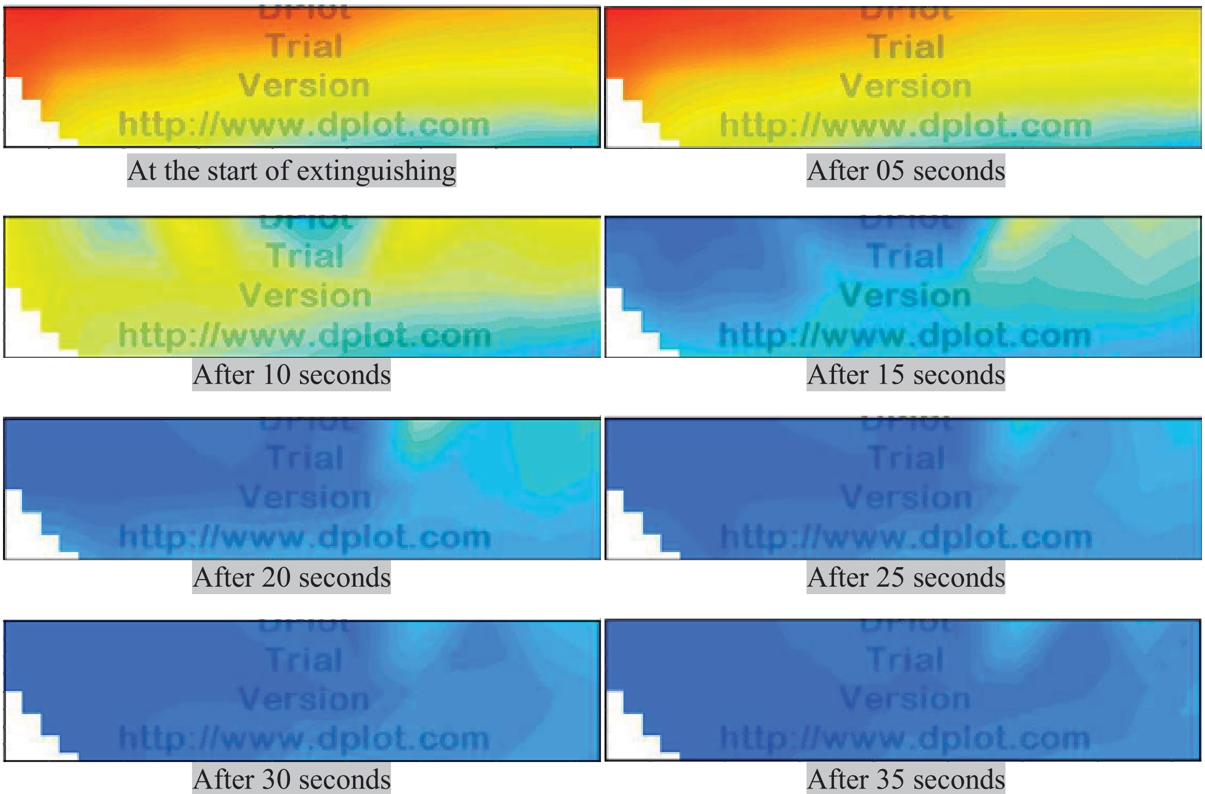


Figure 48. Evolution of the temperatures on lengthwise slice of the container, during extinguishment, for scenario 2

We can see here a very thick hot layer, and quite no blue zone anymore on the floor. All the volume exceeds 200 °C. The 2 first slides are similar, nothing seems to happen. After 10 seconds we are fully involved in the cooling stage, the temperature layers are rising. After 15 seconds, the compartment is below 300 °C everywhere, with again a hotter pocket beside the curtain, which probably deflects the flows of water mist, causing the remaining yellow zone.
At this stage the fire area looks the coolest, which would sustain the theory of the mist travelling until the dead end of the compartment, before a return to the front wall, where the mist is projected. This explanation is then confirmed in its statements, by the progress of this cold zone from the fire area to the front, on the later screens.
The entire compartment remains totally “blue” after 35 seconds, like on Scenario 1.

- **<u>Scenario 3: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m²) and with openings (2.71 m²).</u>**

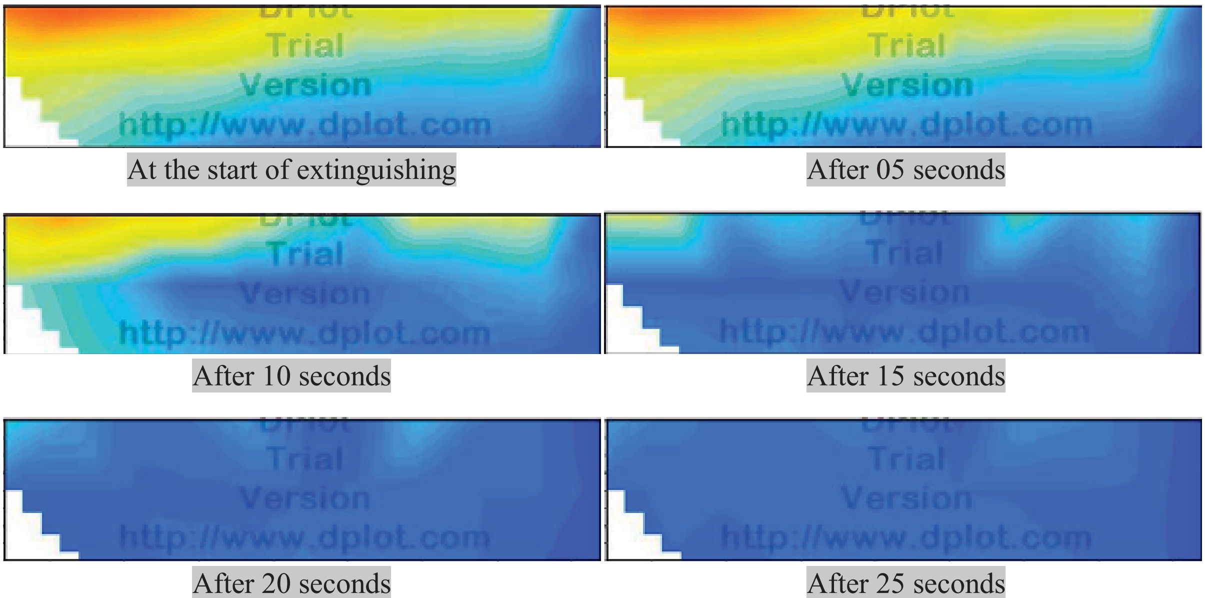


Figure 49. Evolution of the temperatures on lengthwise slice of the container, during extinguishment, for scenario 3

Here, the smoke layer is not as hot as in the scenarios with closed compartment; there is almost no red zone on the ceiling. One other interesting element is noticeable, already on the first slide, which is the influence of the door, "cutting" the hot layer. It is visible by the sudden raising of the blue zone, taking all the height of the enclosure, on the right side. Again, nothing happens during the 5 seconds at the beginning, which confirms the sort of "plateau" seen previously on all the curves. After 10 seconds, there is a sharp rise of the hot layer, as well as a gap of "cold inflow" in the yellow layer, due to the second opening; showing that the air is sucked into the container.

The entire volume get its blue colour within 25 seconds, and we can highlight the wave of fresh air coming in from the door, represented by the dark blue bubble popping from the right side of the slice.

- **<u>Scenario 4: Cutting Extinguisher at normal flow rate (56 L/min), reduced combustible load (8.4 m²) and no openings (0.192 m²).</u>**

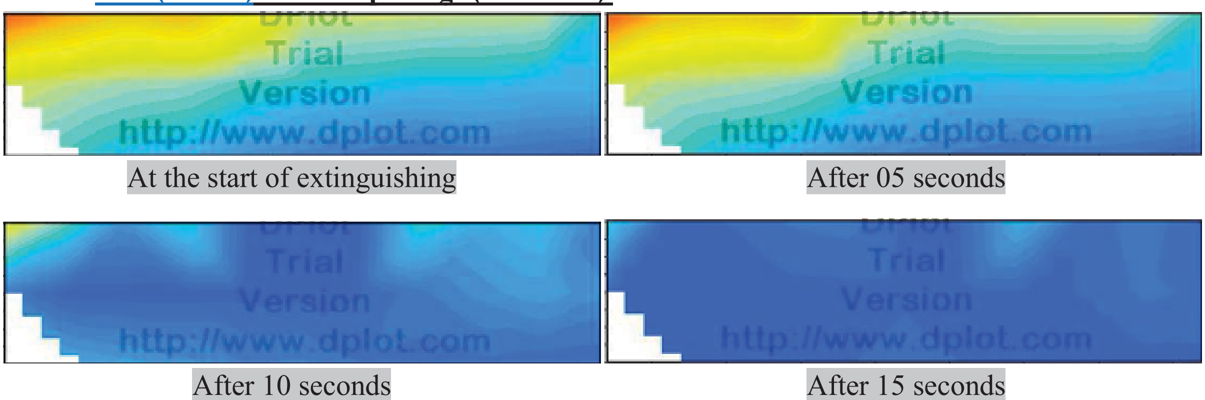
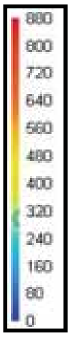


Figure 50. Evolution of the temperatures on lengthwise slice of the container, during extinguishment, for scenario 4



Scenario 4 is the perfect witness of the influence of combustible fuel; the majority of the compartment is below 300°C up to 1.50 m high, and the floor level does not exceed 100°C. Again, we have 5 seconds latency before seeing any visible evolution of the temperatures. And only five seconds later, the hot layer has been sucked up to the ceiling, leaving the rest of the compartment below 200 °C. The compartment becomes entirely blue, within 15 seconds, requiring 14 kg of water.

- **Scenario 6: Cutting Extinguisher at reduced flow rate (28 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)**

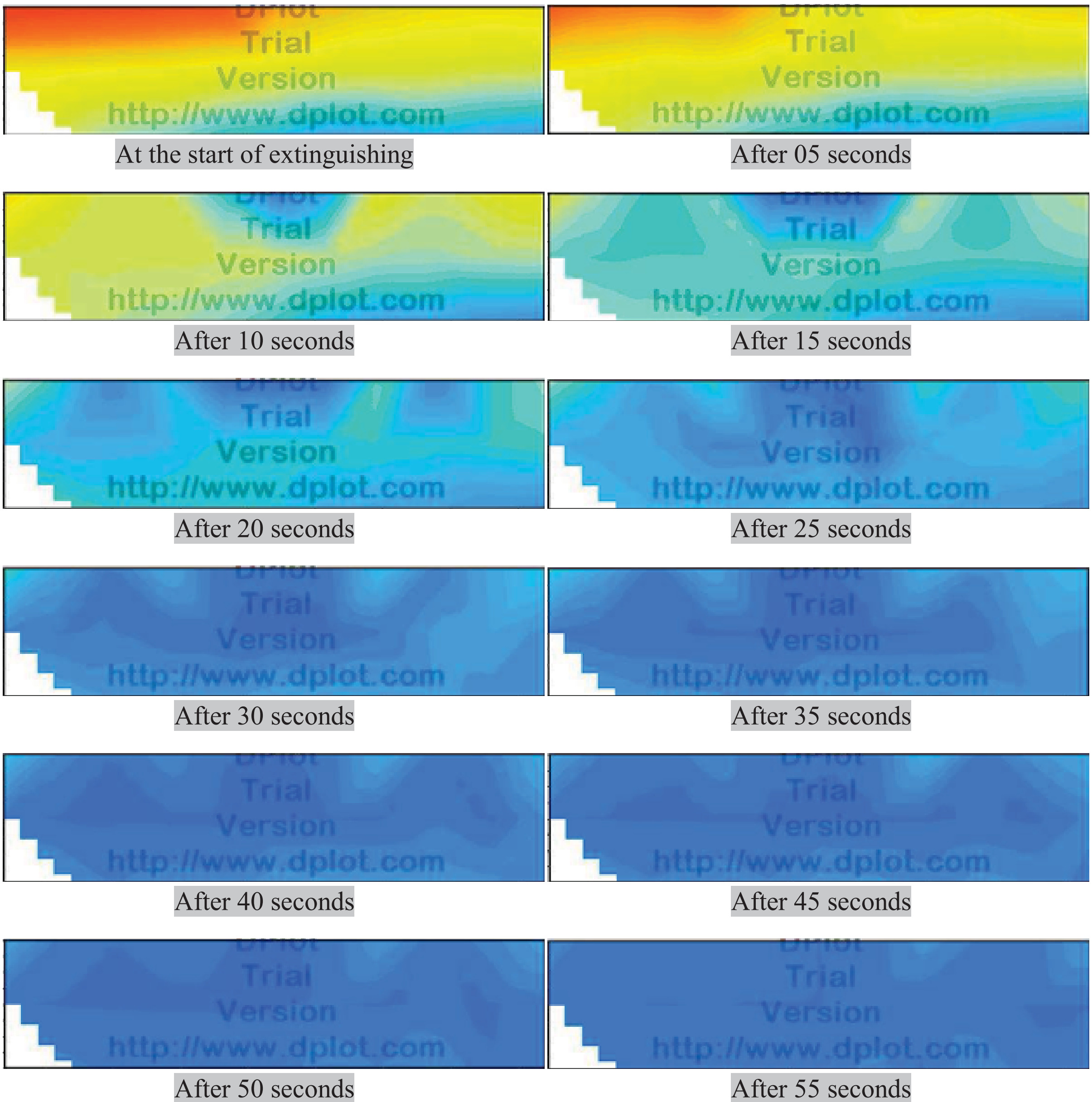


Figure 51. Evolution of the temperatures on lengthwise slice of the container, during extinguishment, for scenario 6

The combustible load is on its maximum, and the compartment is closed before extinguishing, which is clearly deductible by the presence this time of an imposing hot zone of temperatures higher than 500 °C, and a grazing air supply to the fire area. Unlike the other scenarios, we can notice here an immediate action of the water mist penetration, by a reduction of the hottest layer (800 °C, in red on

the slices). The stratification is not disturbed significantly. After 15 seconds, the compartment is below 300 °C, and a cold pocket is visible in the upper part, middle of the length.
The temperature drop is not as fast as the other scenarios, and not less than 55 seconds are required to obtain the desired blue colour, showing an average temperature of approximately 100 °C involving the entire volume. However, since the Cutting Extinguisher's flow rate capacity is reduced to 28 L/min, the water amount used stays below 26 Litres.

➔ Unlike on a single point measurement, the study of an entire surface gives much more information about the global flooding properties of the water mist. On all the scenarios, the compartment is evenly cooled down, which is evidence of the mist expansion over the entire volume.

Regarding the amount of water used, it is clear that the amount is astonishingly low, in comparison to other fire fighting medium. Regardless of the scenario, a safe environment is created (shown by the volume getting completely blue, meaning that the temperature are about 100 °C) with spraying a maximum 33 Litres. Distributed over a volume of 63.7 m^3, the water amount pulverized is about 0.5 kg of water per cubic metre. And even if no vaporization would occur, the remaining water on the floor would stay below 1.3 mm ($water\ height = \frac{volume\ injected}{floor\ area} = \frac{0.0327}{26.108} = 1.25 \times 10^{-3}\ m$), which is small Moreover, since we actually have vaporization, which is not far from a yield of 100%, regarding the volume cooled, there is no water damage at all.

Concerning the comparison of the scenarios, it appears that scenario 1 and 2 are showing a similar event, at the same period of time, which confirms the credibility of the further comparison of the other scenarios. Scenario 3, for example, needs a very low period of time to be extinguished, in comparison with 1 and 2, and shows an interesting phenomenon, of localized cold bubbles appearing just at the exact position of the openings. This could not be visible if the flow were directed to outside, since the out coming gases would be hot. This means then, that there a flow of air from outside, coming into the compartment.

The influence of combustible fuel, from looking at the slices of scenario 4, is definitely improved, in the sense that the lower the burning area, the easier it is to extinguish. Indeed, it did not take even half of the time to get a "blue" container with a 8.4 m^2 burning area, than in situation with 12.8 m^2.

Same observations for the flow rate; as higher the flow rate, the faster the enclosure cooled down. However, it is important to note that if the flow rate influences on the extinguishing time, it is not the case with the amount of water. There is no significant difference in the quantity of water needed. By the way, this point would be interesting to study further, in order to assess if the extinguishing time only depends on the water amount, or if the relationship of instant flow rate is still important to achieve flame extinguishing.

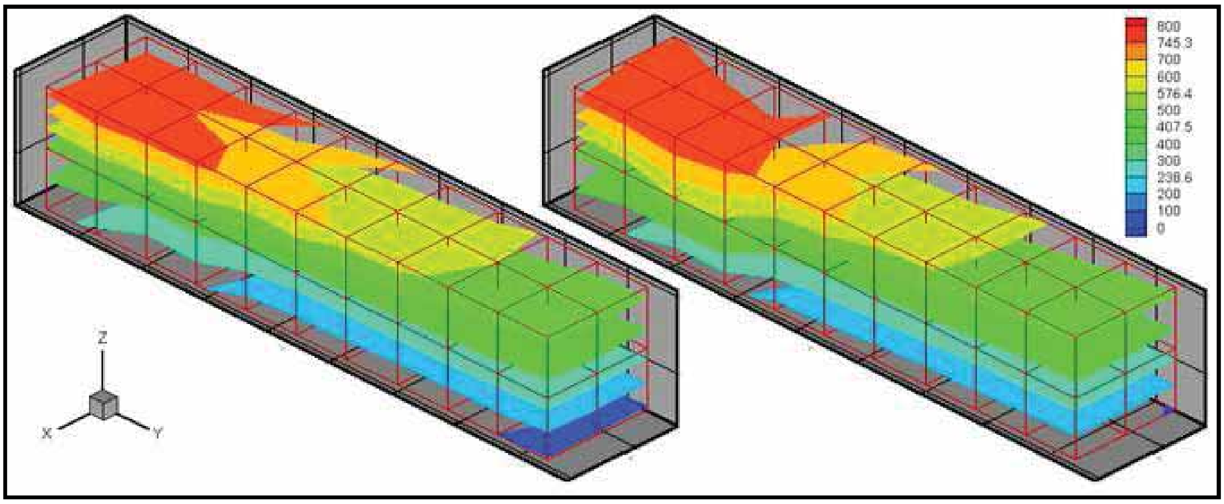
Finally, as far as we could see on the lengthwise slices, there was no noticeable loss of stratification of the temperature layers. Keeping in mind the route taken by oxygen to supply the fire, this would mean that there is no homogenization which could mix this "breathable air layer" on the floor with smoke and combustion gases , and cause both a great premixed flame volume, and suppress a potential "survival zone" for a lying victim.

However, an evolution of the mist penetration and extinguishing on three dimensions provides a better understanding of the behaviour of the different temperature layers, which we will focus on next section.

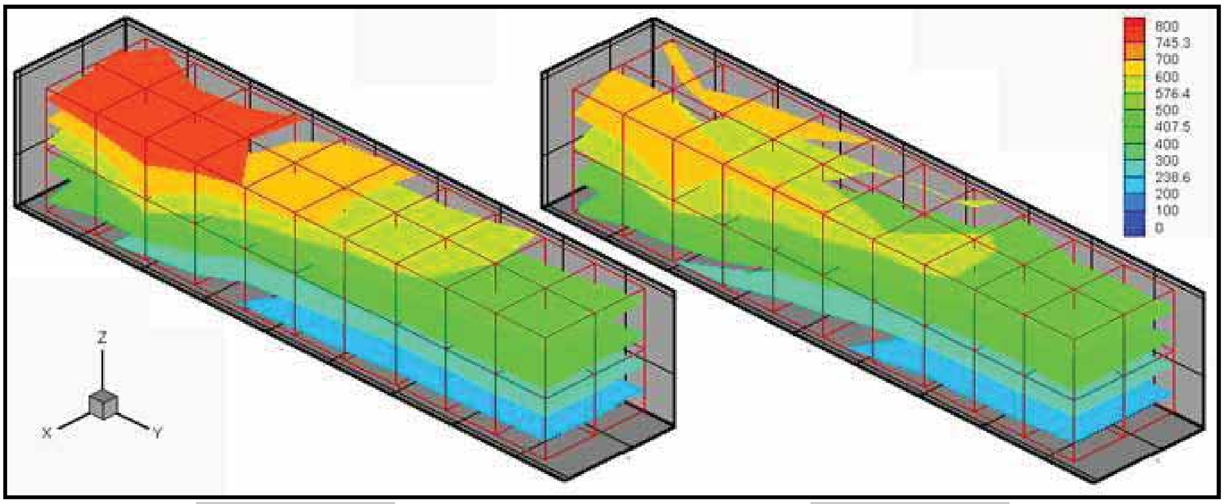
Stratification concerns

In order to get a better visual aspect of the behaviour of the temperature layers together, we constructed the volumetric stratification of the temperatures, varying in function of the different extinguishing times. Please take care on the scale, which can be slightly different from one scenario to another. Remember also that the ISO view shown here removes the front and left wall, in order to see the inside, thus placing the fire on the left, and the water income on the right part of the compartment.

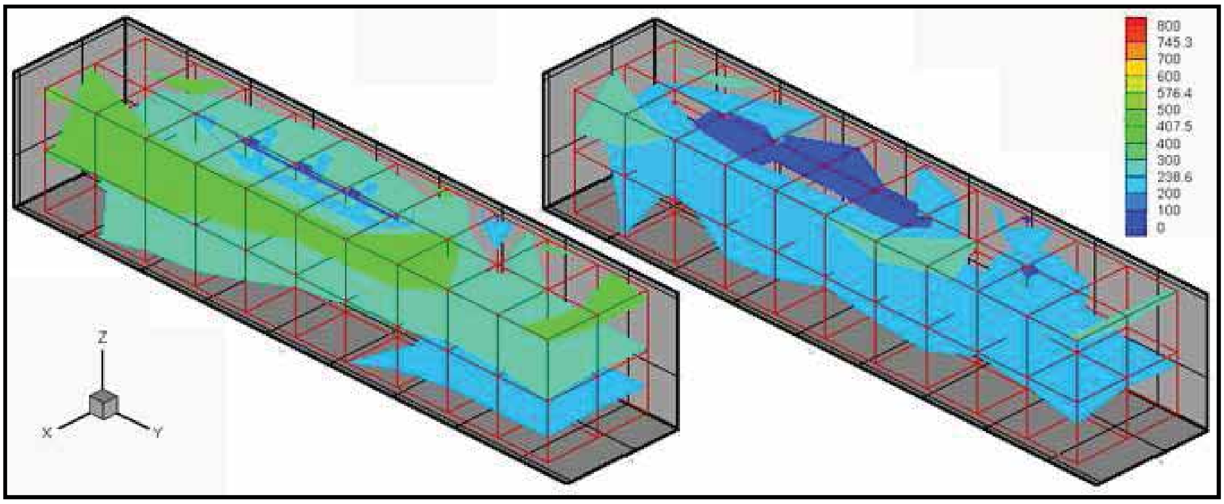
- **<u>Scenario 1: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)</u>**



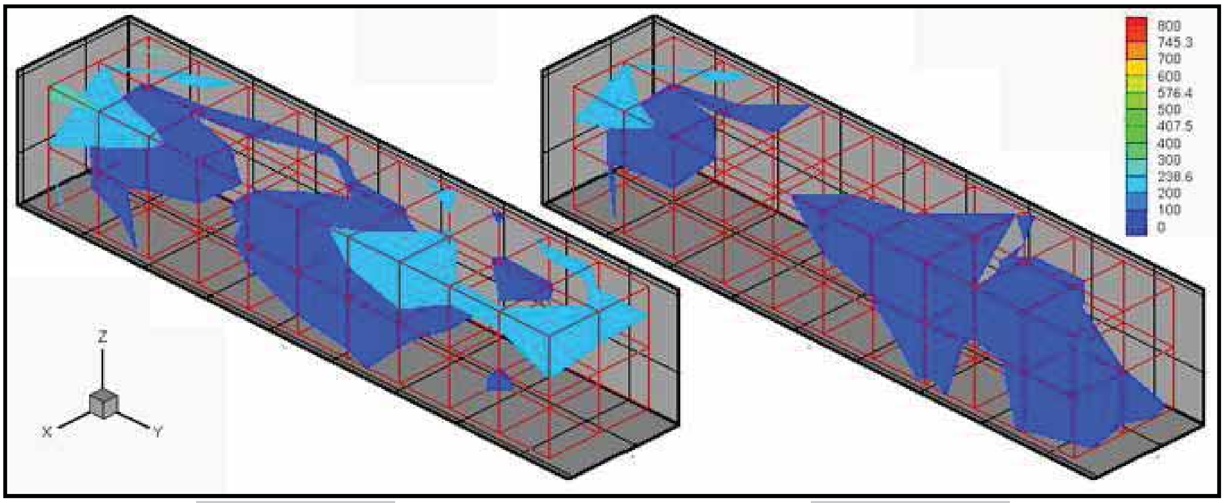
At the start of extinguishing — After 05 seconds



After 10 seconds — After 15 seconds



After 20 seconds After 25 seconds



After 30 seconds After 35 seconds

Figure 52. Evolution of temperatures stratification during extinguishment for Scenario 1

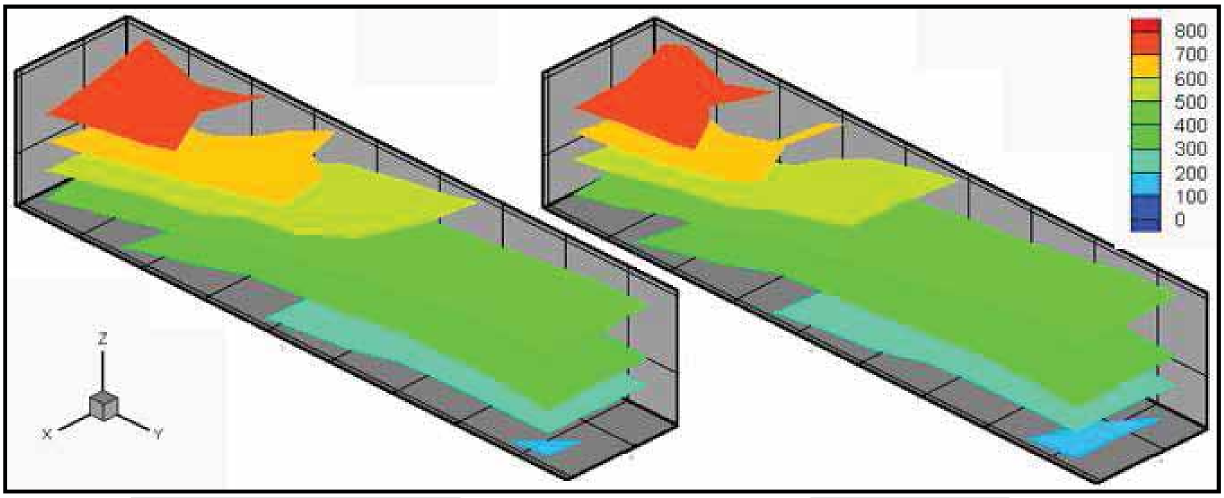
We can see a perfect linear stratification at the beginning, with even a small floor layer below 100°C, represented by the dark blue surface near the front wall.

The water mist causes a contraction at the entrance of the fire area (at 8.00 metres from the nozzle); the layers tend to fall slightly. The phenomenon is increased at 10 seconds, and the real cooling occurs at 15 seconds.

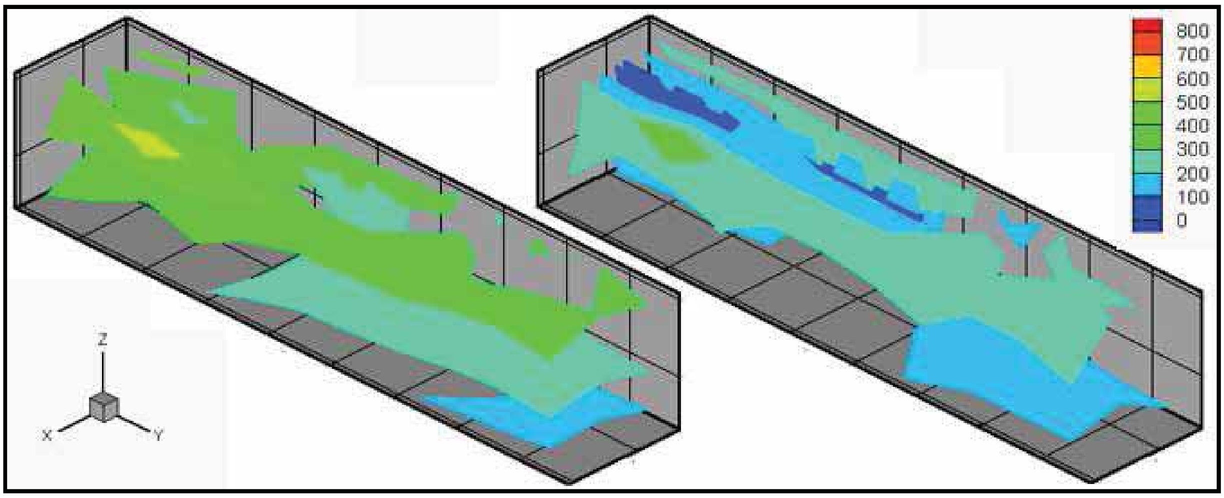
The 700 °C strata then disappears and leave room for a consistent atmosphere at 500-600 °C. The layers continue to rise, but have lost their nice linearity. The boundaries of the ISO surfaces are buoyant, but still established in the length of the volume.

After 35 seconds, the entire compartment is dark blue, which means that the temperatures in the volume are below 100 °C.

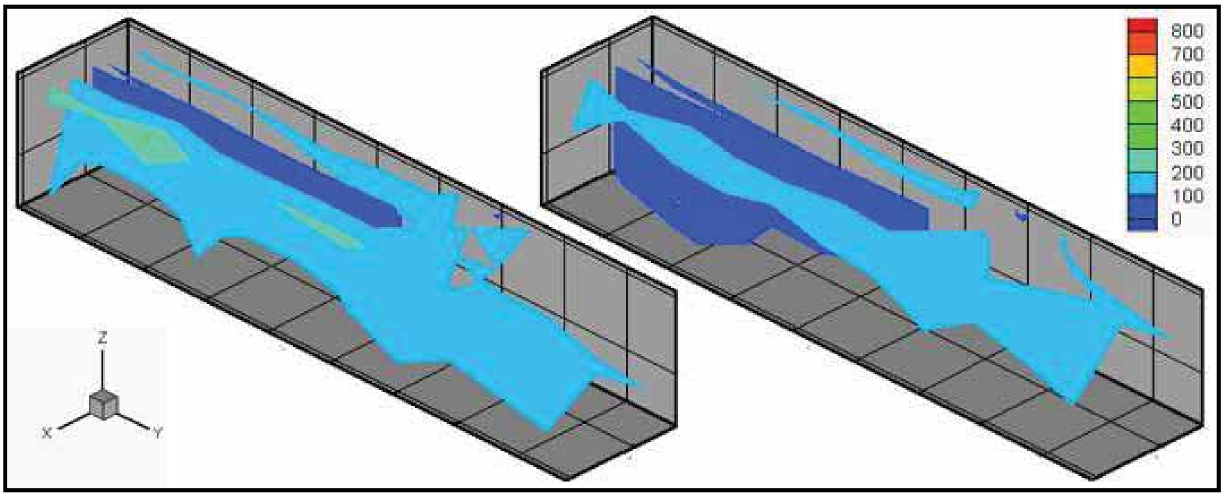
- **<u>Scenario 2: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)</u>**



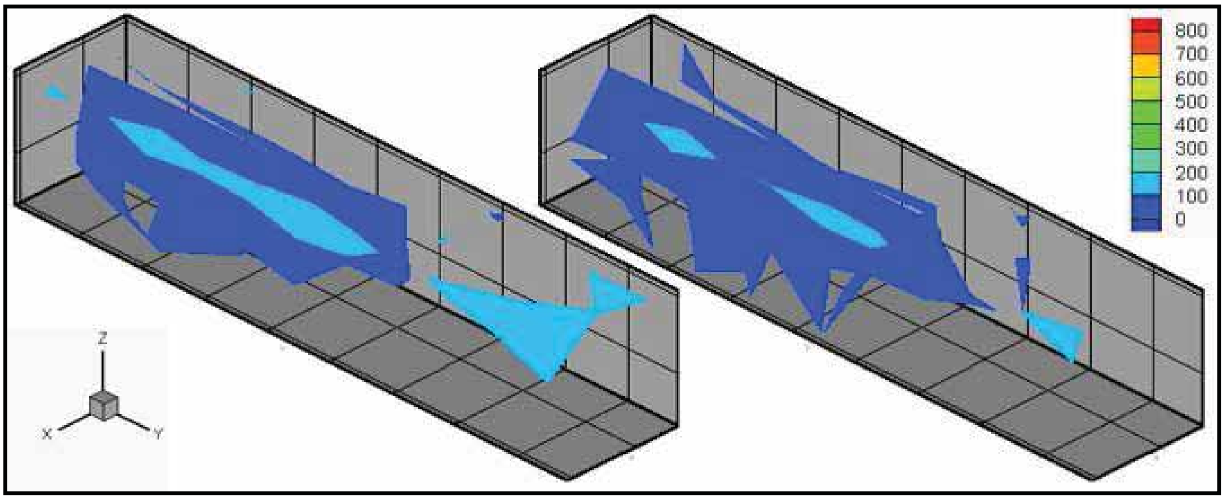
At the start of extinguishing
After 05 seconds



After 10 seconds
After 15 seconds



After 20 seconds
After 25 seconds



After 30 seconds After 35 seconds

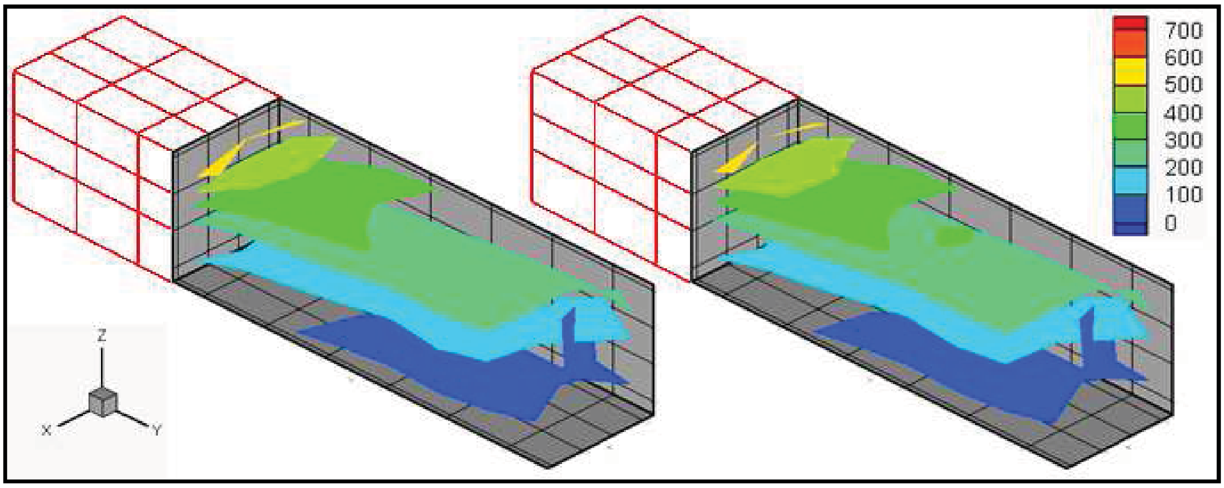
Figure 53. Evolution of temperatures stratification during extinguishment for Scenario 2

In the second scenario, (which follows exactly the same experimental protocol as Scenario 1) also has these linear layers, but this time less horizontally distributed: they tend to rise from the bottom floor level to the ceiling height.

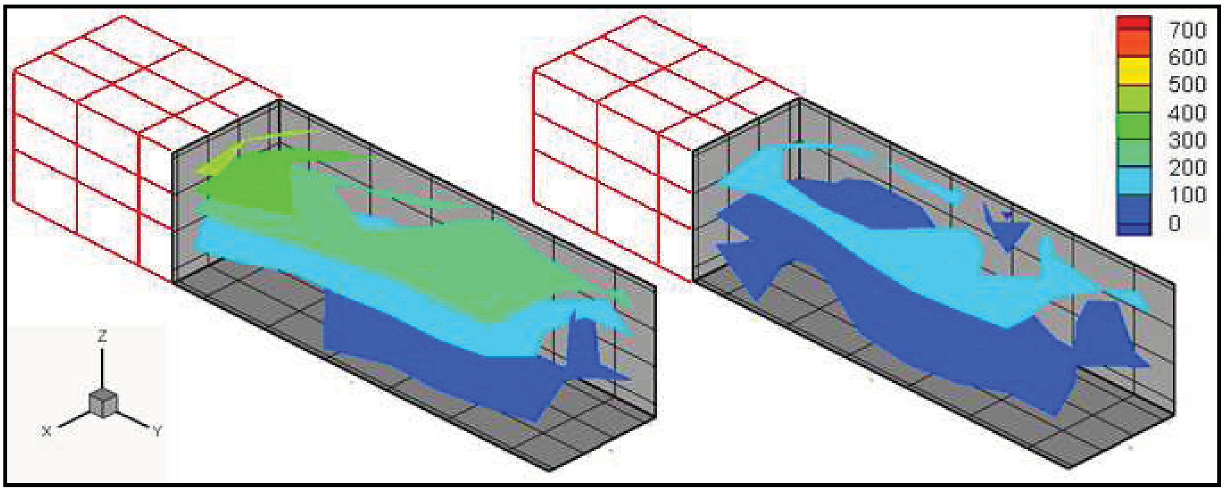
5 seconds after the start of extinguishing, the layers again suffers this sort of contraction which crumples the layers at 8.0 metres, but without disturbing the lower layers. Water has a visible effect after 10 seconds, by causing the layers to rise, and we can even imagine the spray pattern around the centreline in blue, which is the evidence of a very cold (water at 25 °C) fluid at this position.

The cooling progressively continues until 35 seconds, where all the compartment is dark blue, and which corresponds to the same time delay than on the first scenario.

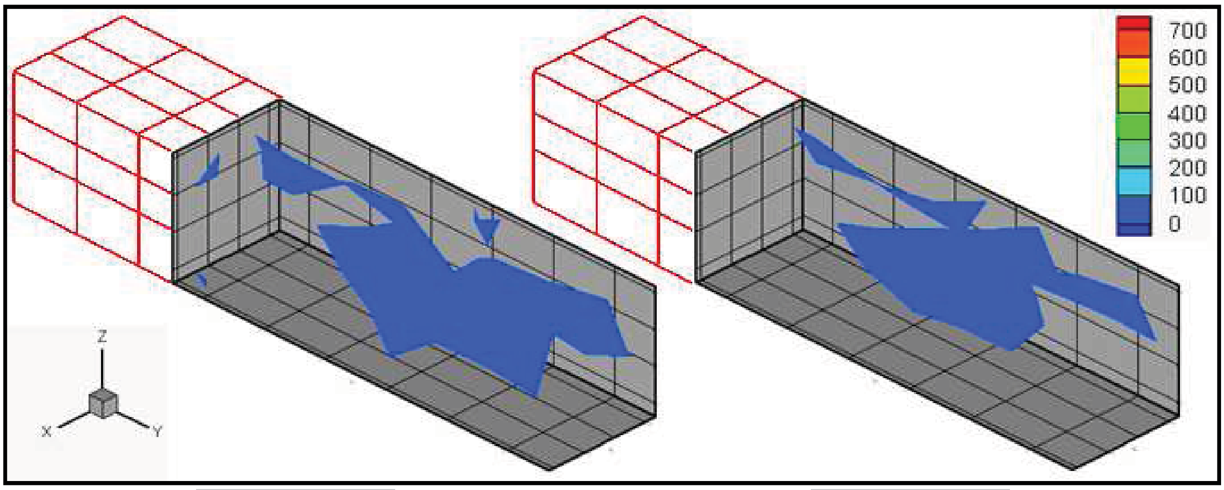
- **Scenario 3: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and with openings (2.71 m^2).**



At the start of extinguishing After 05 seconds



After 10 seconds After 15 seconds



After 20 seconds After 25 seconds

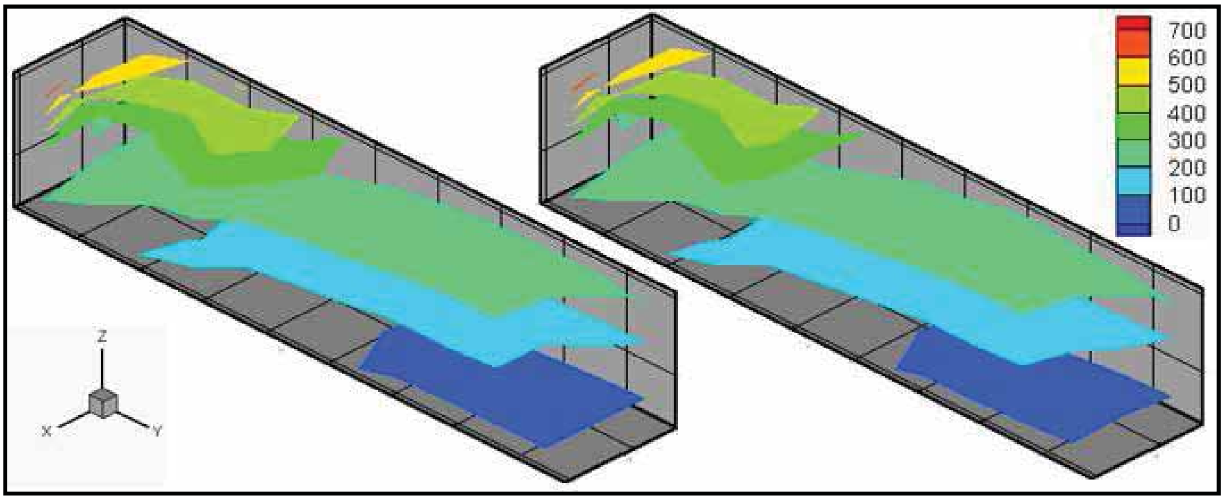
Figure 54. Evolution of temperatures stratification during extinguishment for Scenario 3

Scenario 3 was the last burning of the experimental session, and due to a lot of stress and solicitations, a consequent part of the thermocouples did not respond anymore; so it was decided not to show the first three slices (at the location of the red mesh), which were suffering from a lack of response from10 TC out of 27.

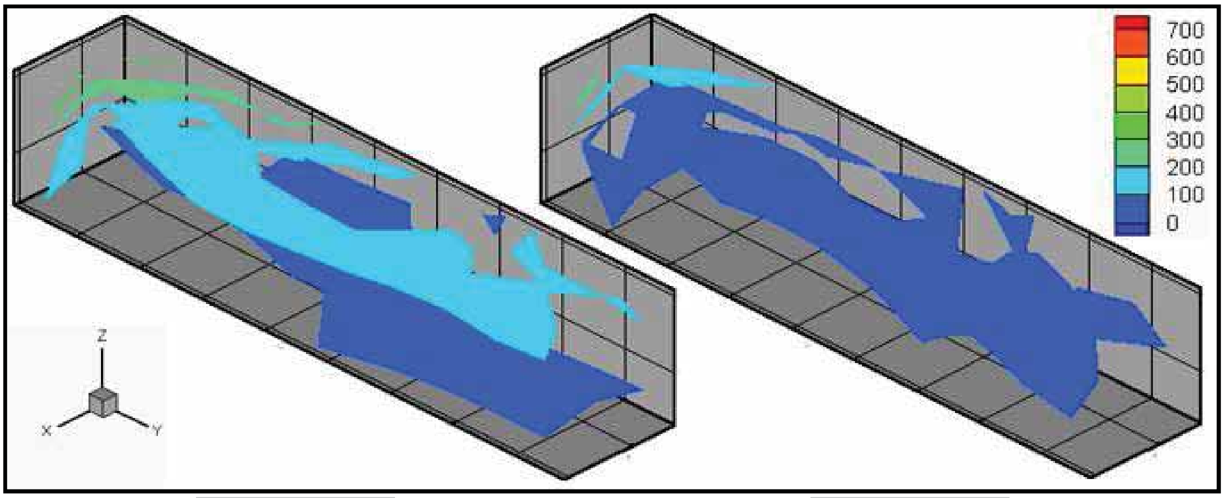
Concerning the analysis of the views; the cooling causes a rise of the temperature layers, and we can again notice the influence of the window, by presence of the hole dug into the 300 °C strata at 10 seconds, and the appearance of the triangle of very fresh air coming in (2 triangles, against the right wall, in dark, and very dark blue, meaning temperatures below 100 and 30°C) at 15 seconds.

The layers are buoyant, but still keeping certain horizontality, until the compartment gets blue in its entirety within 20 seconds.

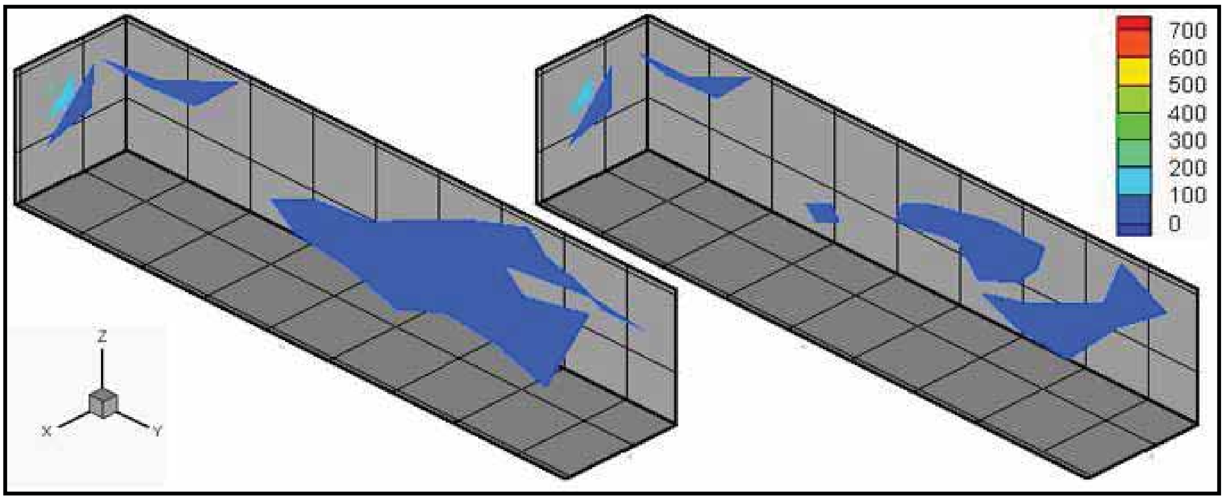
- **Scenario 4: Cutting Extinguisher at normal flow rate (56 L/min), reduced combustible load (8.4 m^2) and no openings (0.192 m^2).**



At the start of extinguishing After 05 seconds



After 10 seconds After 15 seconds



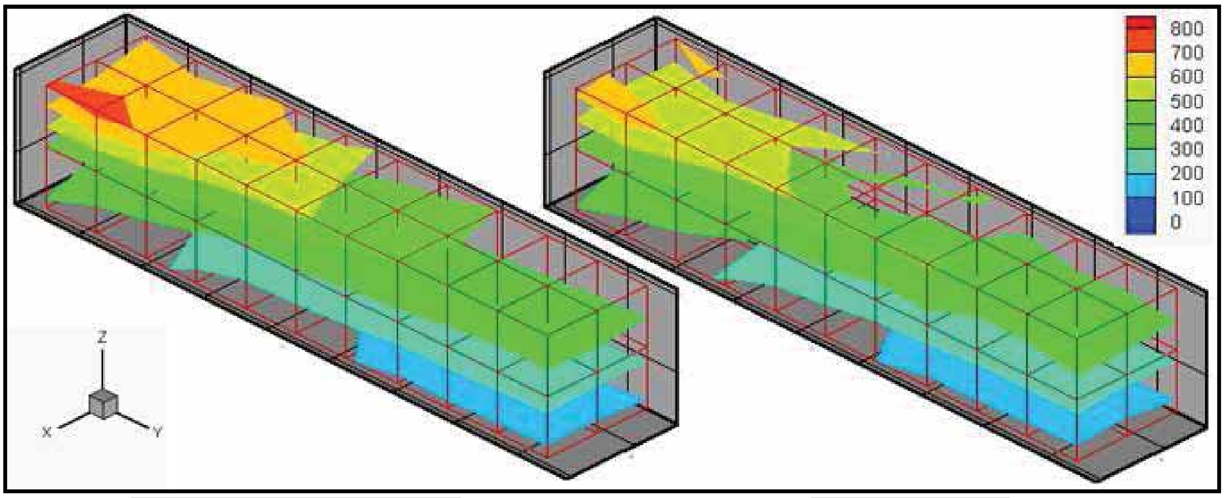
After 20 seconds After 25 seconds

Figure 55. Evolution of temperatures stratification during extinguishment for Scenario 4

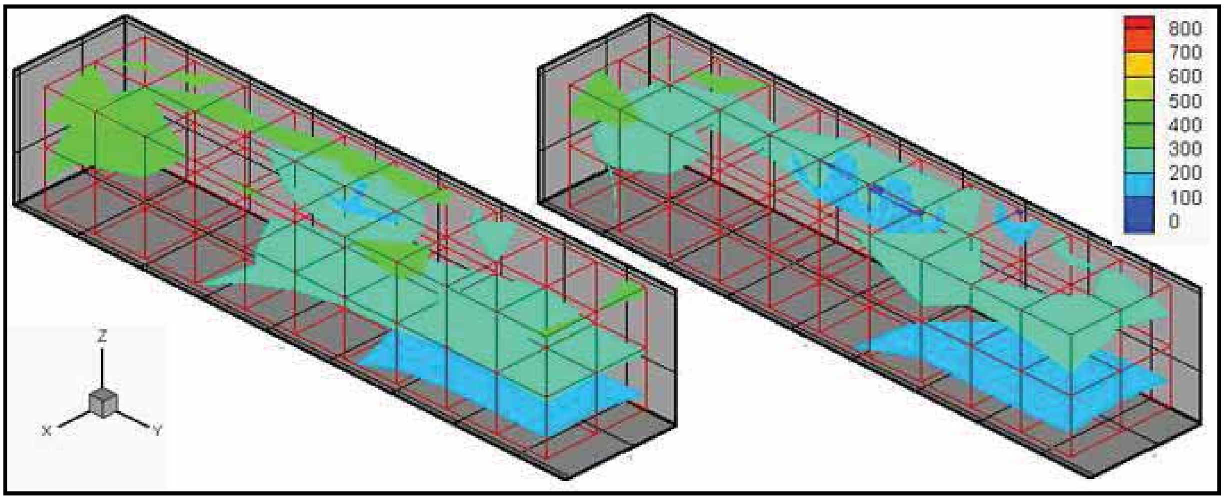
Scenario 4 is the witness of the influence of combustible fuel. As shown on the fuel arrangement characteristics, the reduced fuel area is having most of its combustible on the ceiling, bottom and right wall. It is visible by looking at the hottest layers, which seem to be coming from the bottom right corner. Unlike the lower strata, those representing the higher temperatures are quite buoyant from the beginning of extinguishing.

During the spraying, all the layers are rising without mixing; they keep their integrity and leave progressively more room until all that remains is the 100 °C ISO surface, after 15 seconds.

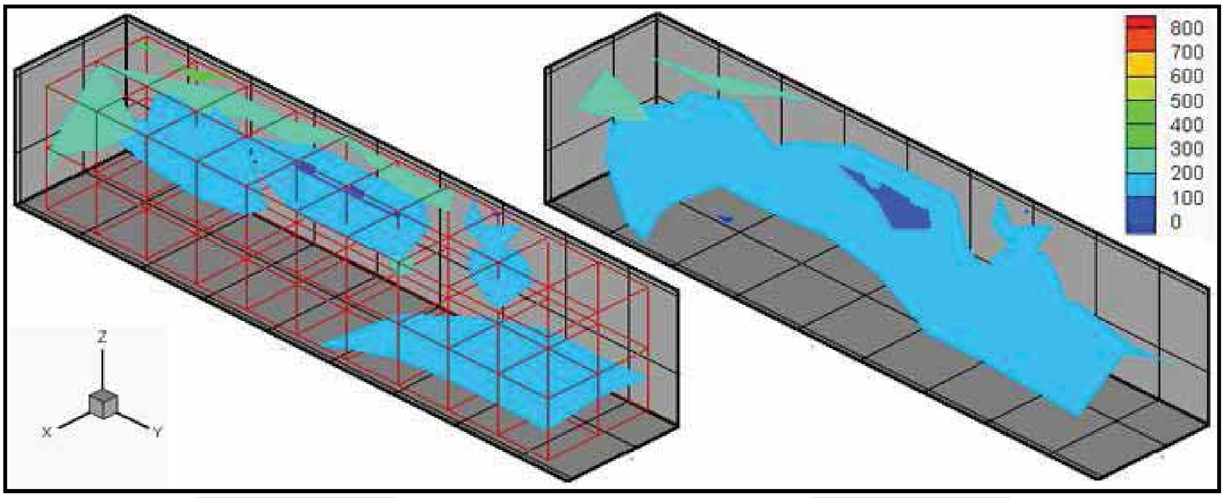
- **Scenario 6: Cutting Extinguisher at reduced flow rate (28 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)**



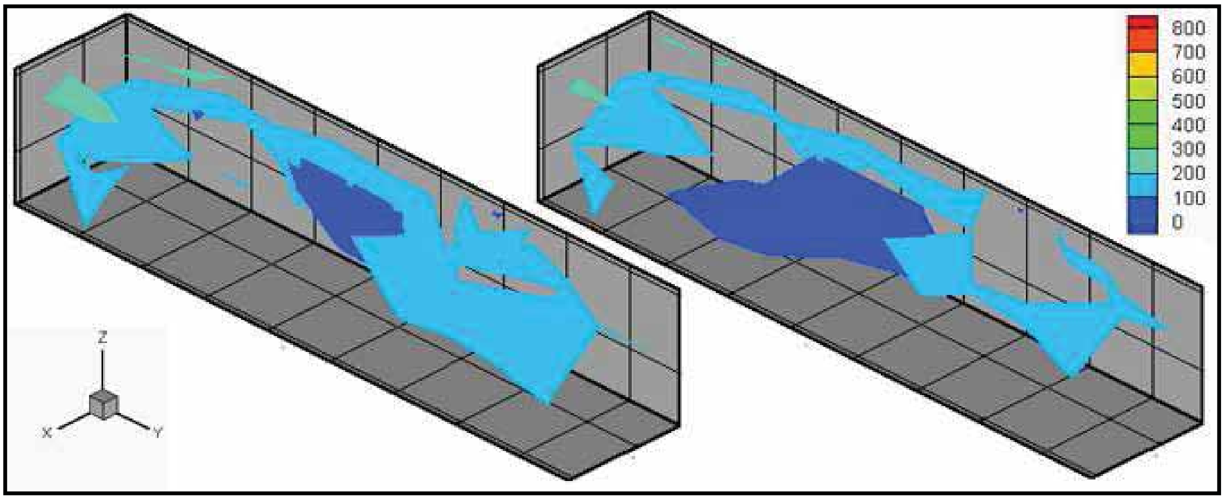
At the start of extinguishing | After 05 seconds



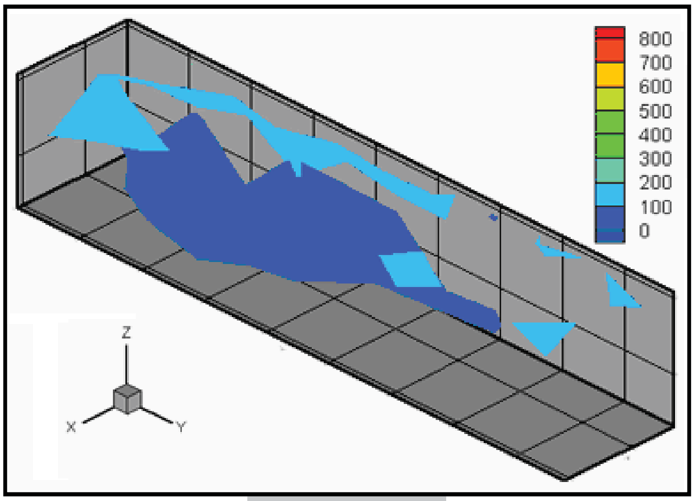
After 10 seconds | After 15 seconds



After 20 seconds After 25 seconds



After 30 seconds After 35 seconds



After 40 seconds

Figure 56. Evolution of temperatures stratification during extinguishment for Scenario 6

On the last scenario, we can also notice a perfect temperature stratification; nice even and horizontal. When the water mist penetrates the compartment, we can imagine the location of the spray pattern: at 5 seconds, there is a hole which seems to being dug in the centre of the volume, and "eats" the layers. The lower strata are not affected at all at this time.

10 seconds after beginning, the upper layers are disappearing, and the layers are wavy, until after 40 seconds, at which time the coolest dark blue ISO surface is dominating.

➔ Regardless to the scenario, we can remark that the layers are quite horizontal, and evenly distributed. There is probably a small mixing, shown by the strata crumpling, but it appears not to be so significant, since even if the layers are a bit contracted and wavy at some location, and at particular time steps:`
    - They never intersect
    - They never fall down to the floor
    - They keep their horizontal shape at any time, despite the buoyancies
    - The "survival layer" remains present on the floor at any time

Post-spraying fire behaviour

The Cutting Extinguisher is not a fixed system. It is a hand held lance, operated by fire fighters. Due to its intrinsic characteristics, like its ability to penetrate every type of structure, a rational tactical use induces us to take into account that the nozzle is not the only tool used in the course of a fire response operation, but a penetration in the involved compartment is necessary, to do a reconnaissance of the volume, finish flooding the charring products, and check for the presence of potential victims.
It appears then that a certain period of time could occur between the end of spraying in the compartment, which maintains control of the volume, and the discovery of the fire location by the BA Team entering. We propose in this section to have a look at the evolution of the situation inside the compartment, after the end of extinguishing, as allowed by the experimental protocol that required waiting at least three minutes after extinguishing, before stopping the data recording.
In order to support our words, we base our analysis on the evolution of temperature and video record taken on certain scenarios.
The temperature curves used are taken from the data of TC 2, which is midway of the width, 0.4 m from the end, and 2.0 m high. Please also remember that the data logging on Scenario 6 was interrupted during extinguishing. Post-spraying evolution is then not available on this situation.

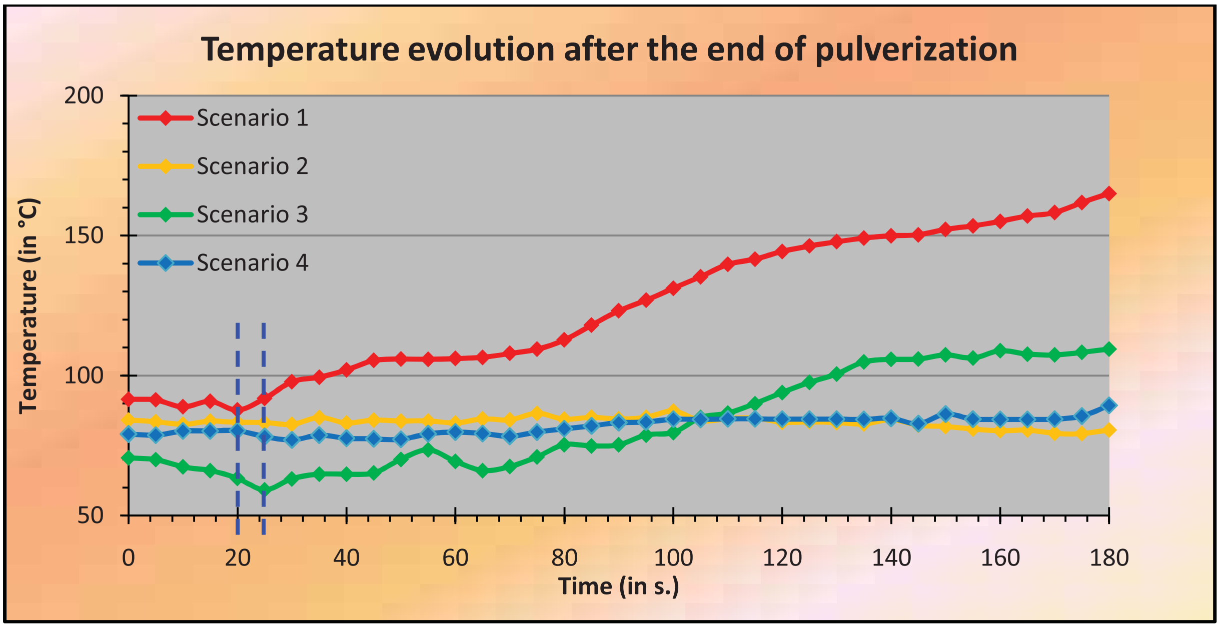


Figure 57. Evolution of the temperatures during the 3 minutes following the end of spraying, on ceiling position above the fire area

Immediately after the spraying period, the temperatures are quite similar, regardless of the influence of various parameters. They are all between 70 and 90 °C. Then it would seem that there is a certain period of afterglow, during which the water spray maintains a stable situation. This could correspond to the time mist remains in the volume (at 2.0 m high, which is the position of TC2), which has to be differentiated with the droplets' lifetime, which is not determinant anymore, since the temperatures are quite low at this stage. We can meet a mean duration of 21 seconds, based on the tendency shown by the curves 1 and 3.

Over the entire period of 180 seconds, the Scenarios 2 and 4 do not rise anymore, meaning by this that the fire does not restart, which is not surprising, since the compartment is closed, and there should be no more oxygen to reactivate the combustion on charring material, like on scenario 3. More astonishing, Scenario 1 seems not to obey this law, and begins to show a temperature rise, which is not dangerous for the fire fighting operations, since even in this case the temperature after 3 minutes does not exceed 170 °C at 2.0 m high.

However, the camera was used during experiment 1, which gives us the opportunity to "see" what really happens in the fire area during this period of time.

Consistent with the presentation of the Compartment Instrumentation section dealing with video record, the Scenario 1 is filmed from position 4. The following pictures are snapshots from the video, taken at intervals of 30 seconds, after the end of spraying.

Figure 58. Fire restart in the compartment after the end of spraying, during Scenario 1

It appears that there is actually a small fire restart, on the bottom down right corner, maybe due to a piece of un-burnt chipboard that fell down. Concerning the oxygen supply, we notice the door frame profile, where light penetrates into the compartment, allowing a small volume of air to enter, and feed this small fire.

- ➔ In the light of these results, we can reasonably conclude that the environment after three minutes of continuous water mist spraying in the studied compartment remains safe for at least three more minutes. Extending our statements, thanks to all the previous analysis, it appears that the water mist produced by the Cutting Extinguisher is a very efficient fire suppressing agent, which enables fire fighters to secure any hazardous environment which could be encountered in compartment fires. It has also to be mentioned that complete extinguishing still has to be done by wetting the remaining charring material, which could restart a small flaming combustion. However, for a BA Team equipped with protective equipment, there is no further danger from Rapid Fire Progress (RFP) phenomenon.

Safety concerns

With no further concerns regarding the fire suppression capabilities of the water mist, this chapter does not respect a pure scientific approach, but tries to answer to some of the constantly asked question, by all the users of the Cutting Extinguisher. These interrogations can be examined in two parts including either life or property safety. However, please note that we still only focus on safety regarding the effects of water mist; and not on the hazards associated with manipulating a high pressure system.

Life safety

In Julien GSELL's paper (The Cutting Extinguisher, presentation, demonstration, tactical and operational use, 2009), one point mentions recommendations concerning the presence of potential victims: *"If the fire location is known, and it is possible to attack from an adjacent room, guide the jet in the upper part of the affected compartment [since it] Is more secure, in the case of victims, who are closer to the floor"*

Thanks to an extensive instrumentation of the compartment, we can consider the impact of water mist spraying at lower stages of the compartment on three main points, which are:

- The progress of visibility and presence of a remaining "breathable atmosphere" at lower level
- The variations of the received heat flux
- The evolution of the floor temperature whilst extinguishing, by planar horizontal slices

Visibility and breathability

During the fire growth, the most tenable area in terms of fresh air supply, free from any smoke and other combustion products, is the lower part of the compartment, due to the convection flows, making the air vein to crawl at the lowest level to the floor. Based on the conclusions concerning stratification, and the **Appendice A3**, we can deduce two main situations that a victim can encounter in the case of a fire:

- Either when the fire is in a closed compartment. The smoke layer is then likely to descend to the floor level, with no fresh air feeding in. The clear layer is non-existent, and there is no renewing fresh air. There is no visibility at all. In that sort of situation, it is very unlikely to have survivors in the compartment. However, if it were the case, of if some BA Team were encountering some difficulties in the room; the use of the Cutting Extinguisher would not worsen the situation, but improve it in terms of contraction of the smoke layer, allowing a larger tenable free space under it, and even a fresh air indrawn, due to under pressure, if the compartment is not completely sealed.
- Or when the fire is in a compartment with openings. In this case there is always a remaining strata of breathable atmosphere on the lowest stage, which may be cool enough, thanks to renewing fresh air, to be of sustainable conditions, and allow life to remain possible. If the Cutting Extinguisher is used in this case, there will be a certain mixing of the smoke, and disturbing of the layers, causing a wavy boundary layer, but without removing the "life

pocket" on the floor. Moreover, the visibility is likely to be improved thanks to gas contraction, and allowing by this way to see some previously hidden openings.

Heat flux.

Let us then study the variations of received heat for a lying body, when water mist is used as an extinguishing medium.
Due to the difficulties generated by carrying out full scale burning inside, the instrumentation of the compartment by the Gardon Gauge radiometer raised several problems, especially concerning the insulation of the wire, and providing efficient water cooling. The Scenario 3 especially suffered from a failure of the cooling system, and did not give any conclusive results. Moreover, despite what has been suggested in the experimental protocol, it was not immediately possible to place it on a 40 cm support. This is why the two first experiments, namely running the scenarios 1 and 2, were carried out with the radiometer being on the floor level (but on same position regarding to length and width, and still targeting the ignition zone). Please note that the times given on the following graph does not correspond to the times recorded for extinguishing.

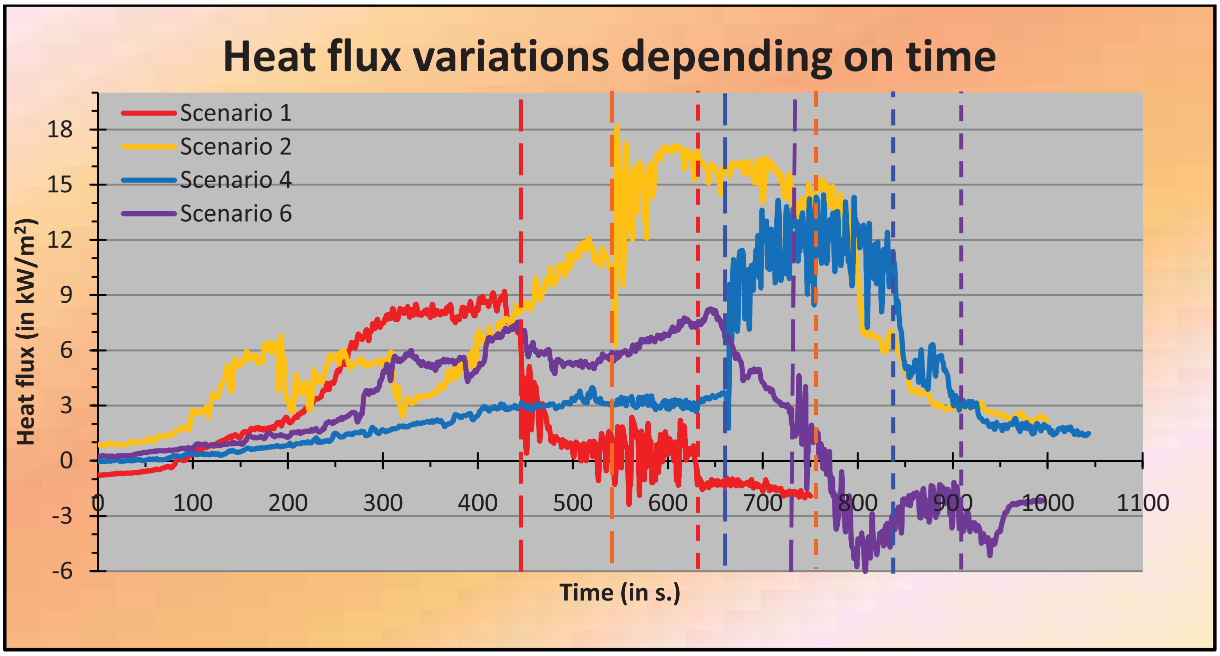


Figure 59. Heat flux measurements for the different scenarios, in function of time

The large dotted lines shows the beginning of water mist spraying, whilst the small dotted ones designate the end of spraying.

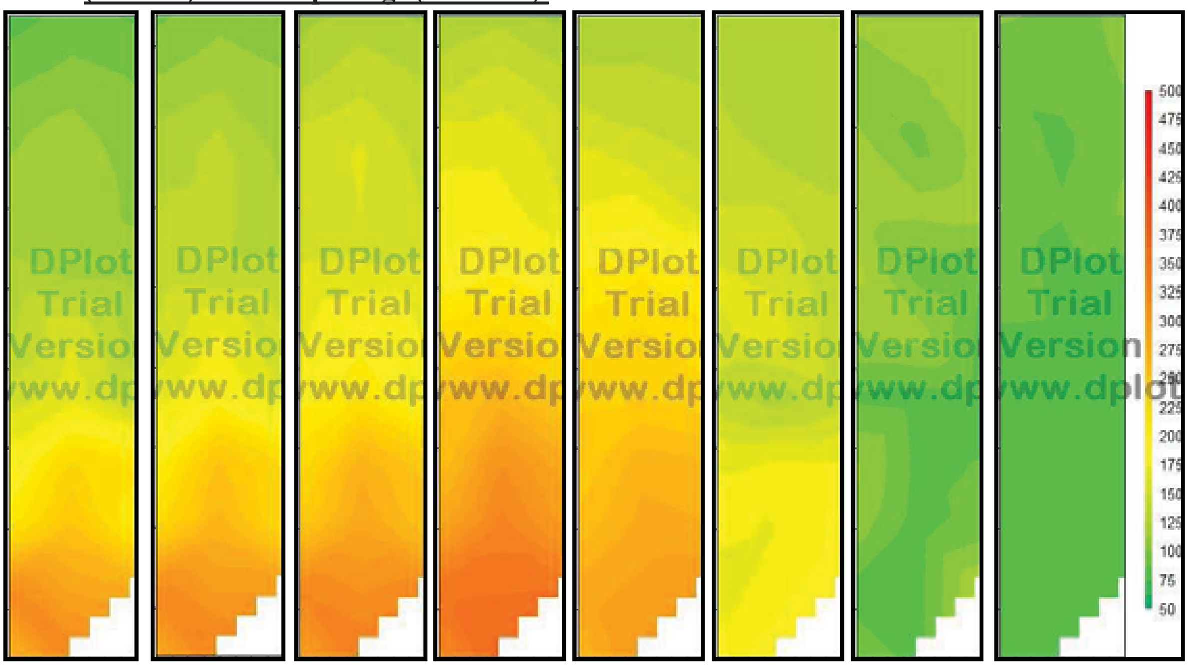
Concerning the general observations, we notice that the range measuring the heat flux for the period of extinguishing looks very disturbed, as the close oscillations show.
Due to the lack of precision, and the variations of location of the radiometer during the burnings, we cannot take into account the values given, in order to compare the scenarios.
However, the tendencies shown by the curves are still usable to deduce in which sense is the heat flux variation when water mist is introduced into an enclosure.
Scenario 1 and 6, where the radiometer was on the floor, show quite a fast drop to zero radiations. Trusting the literature, which demonstrates the radiation shielding effect of water mist, this tendency is very probable. For example, according to P. Andersson and G. Holmstedt (3), a water mist with

droplets of 0.1 mm at a content of 300 g/m^3 absorbs almost all radiations if it has a thickness of 22 cm; reduced to 150 g/m^3, 44 cm is needed; and in the case of the Cutting Extinguisher in this compartment, which has a water content of 44 g/m^3, we need 150 cm.
By contrast, the scenarios 2 and 4 have completely different curve behaviour: the heat flux seems to rise suddenly, when the spraying starts. There is no rational explanation on this, but since the apparatus wire was not insulated, and is transmitting a value in mV it is possible that the water mist caused disturbance on the voltage output.
Anyway, we still can conclude that, regarding the findings of Scenario 1 and 6, a victim lying on the floor would be relieved of the impact of heat flux, thanks to the shielding effect provided by the water mist. This however does not mean that the pain generated by a close fire will be suppressed, which could be due to an exposure to overheated vapour, and cause burns, even if steam does not radiate at all. We will raise the remaining doubts concerning this question by studying, in the next paragraph, the evolution of temperatures.

Temperature

Thanks to the thermocouple meshing in all three dimensions, we can reproduce, using the same process as for the other slices, a horizontal plan. This plan actually represents a cross sectional view of the compartment, as if it was cut in all its length and width, at a height of 0.4 m. The created pictures illustrate the evolution of temperatures thanks to a colour scale (different than previously, since the temperature scale is not the same), showing an amelioration of the conditions (a cooling of the temperatures) when the compartment is turning to green.

- **<u>Scenario 1: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2).</u>**



Start 5 s. 10 s. 15 s. 20 s. 25 s. 30 s. 35 s.

Figure 60. Temperature evolution on an horizontal planar view, at 0.4 m from the floor, for Scenario 1. The fire area is on the lower part, and the front wall, where mist is introduced, is on the top

- **<u>Scenario 2: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2).</u>**

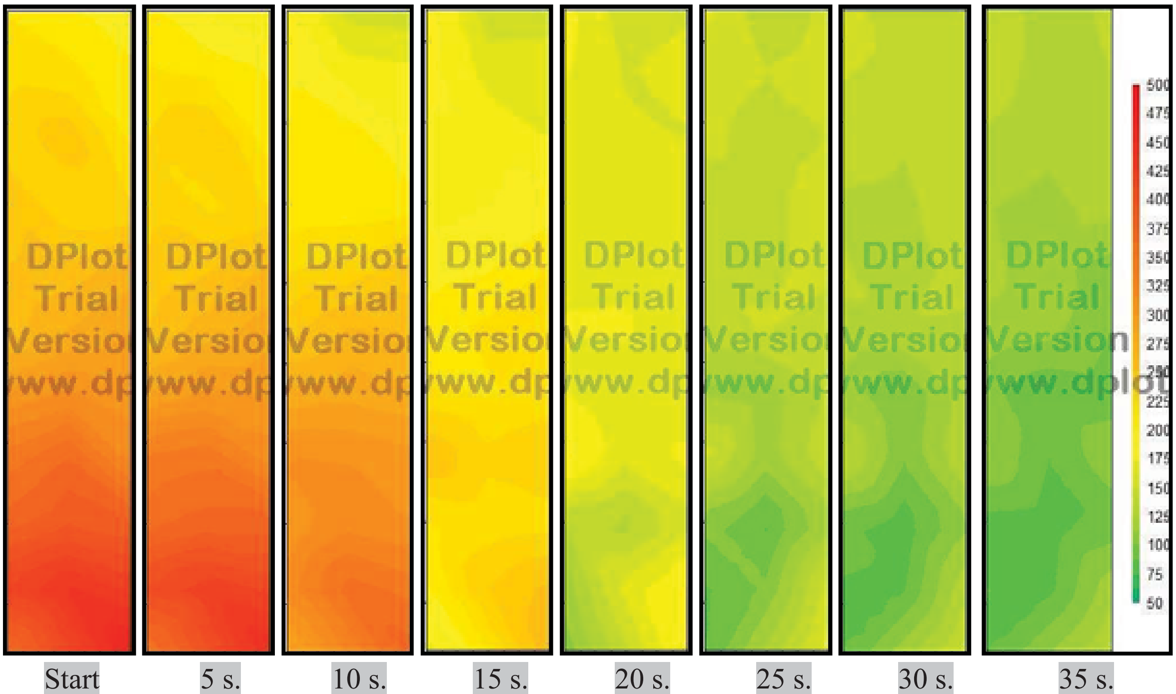


Figure 61. Temperature evolution on an horizontal planar view, at 0.4 m from the floor, for Scenario 2

- **<u>Scenario 3: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and with openings (2.71 m^2).</u>**

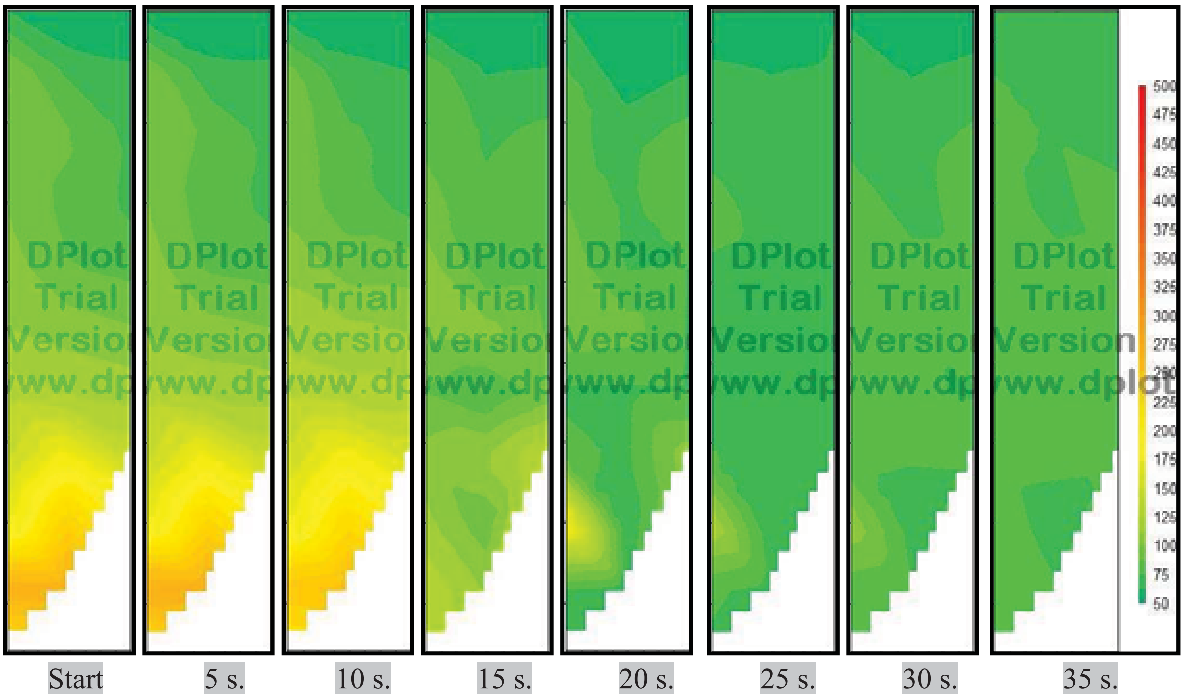


Figure 62. Temperature evolution on an horizontal planar view, at 0.4 m from the floor, for Scenario 3

- **<u>Scenario 4: Cutting Extinguisher at normal flow rate (56 L/min), reduced combustible load (8.4 m²) and no openings (0.192 m²).</u>**

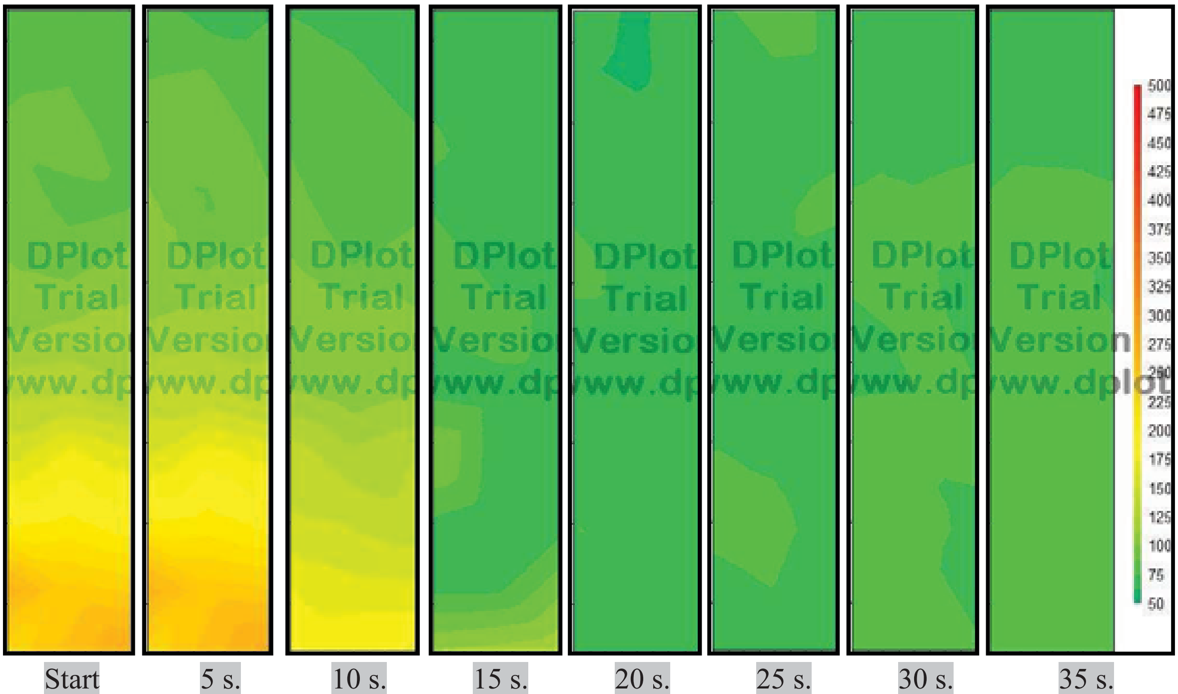


Figure 63. Temperature evolution on an horizontal planar view, at 0.4 m from the floor, for Scenario 4

- **<u>Scenario 6: Cutting Extinguisher at reduced flow rate (28 L/min), full combustible load (12.8 m²) and no openings (0.192 m²)</u>**

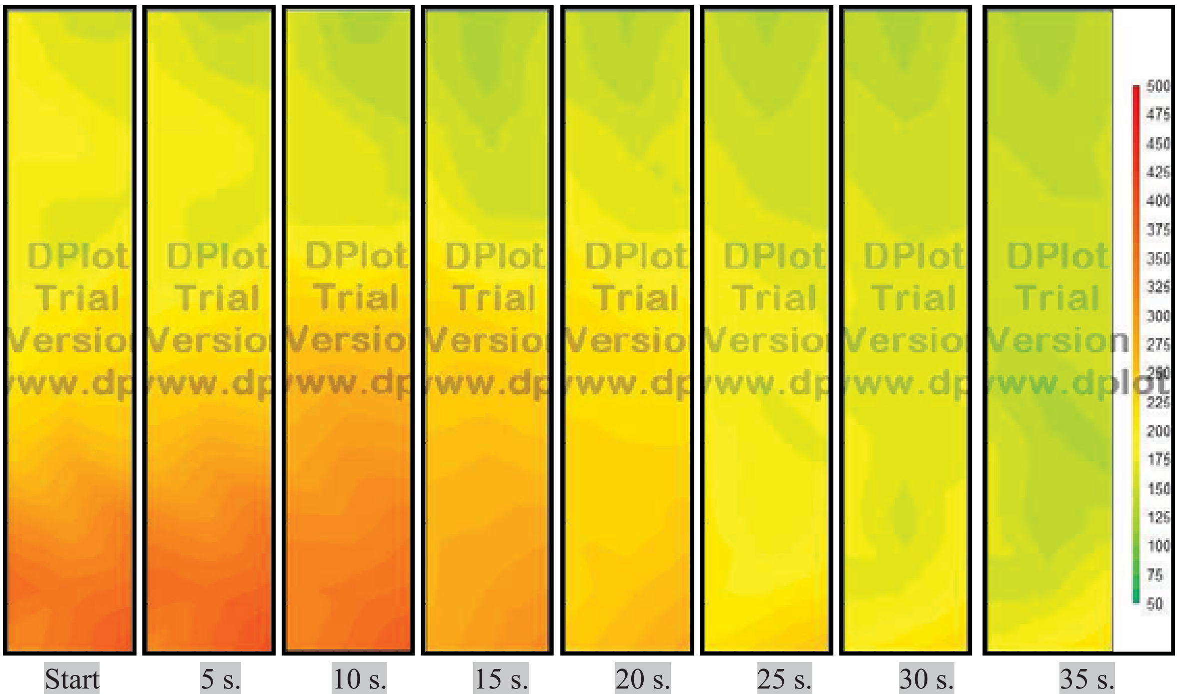


Figure 64. Temperature evolution on an horizontal planar view, at 0.4 m from the floor, for Scenario 4

➔ Except on Scenario 1, where we can observe a slight rebound of the temperatures in direction of the front wall, and the Scenario 6, which needs a longer time to cool down because of a smaller flow rate, making the temperature cooling less visible, all the Scenarios are showing an evenly distributed and gradual temperature decrease over time. Concerning the impact of temperature on a victim, we can remove all doubts about a risk of burn or condition worsening due to the movement of hot gases when the Cutting Extinguisher is used

In the light of the three main parameter studied, which have an impact on maintaining tenable conditions for human life in a compartment involved in fire, we can conclude that the use of water mist, produced by the Cutting Extinguisher in order to tackle the fire, will not have any adverse effect on the health of a victim. Moreover, it will even tend to improve instantly the conditions, both in terms of exposure to heat and temperature, as well as improving visibility, and the maintaining breathable conditions. Of course this is only valid if the Cutting Extinguisher is operated following the tactical and operational recommendations for use.

Property safety

Always taking second place to life safety, property safety is an on-going and very relevant issue relating to the value of damage caused. The aim of extinguishing fires, when we are certain that there are no victims, is to stop the fire progress to reduce to the minimum the costs of the damaged properties. As long as the extinguishing medium causes less damage than if it had not been used, it is worthwhile to extinguish the fire. However, by improving the methodology of extinguishing fire, we can significantly reduce damage in all cases, so every fire is worth tackling

In fire protection engineering, one of the major advantages of water mist compared to traditional sprinkler is actually to reduce the water damage to the minimum when extinguishing fires. In the context of fire fighting, which induces human intervention, the possibility of using water mist, instead of standard fog nozzle, is the assurance of much less water damage.

The Cutting Extinguisher was used for 180 seconds, following the experimental protocol, and therefore spread 168 litres of water within these 3 minutes. But, considering the times required to achieve a cooling of the compartment down to a safe temperature, where there is no more risk of Rapid Fire Progress, we obtained periods of 35 seconds for the worst case scenario. This corresponds to a use of less than 33 litres of water, in a compartment of 63.7 cubic metres. Assuming no water evaporation and entire runoff to the floor, the height of the puddle would be smaller than 1.3 mm. In a fire situation, with an overheated compartment environment, it is likely there will be absolutely no water remaining on the floor after this spraying time.

The small flow rate of the Cutting Extinguisher, associated with an atomisation of water into droplets smaller than 0.1 mm diameter, therefore causes no damage resulting from the use of water. This is valid in the case where the jet has enough distance to allow the inner core of water to break up properly into mist, which occurs at 5 metres.

The second fear of most of the novices regarding the use of water mist is the ability of expanding steam, generated by water evaporation, to cause over pressures capable of breaking windows, or even blast the lung of a victim or a fire fighter. This apprehension is further reinforced because of the high velocity of the water jet produced by the Cutting Extinguisher.

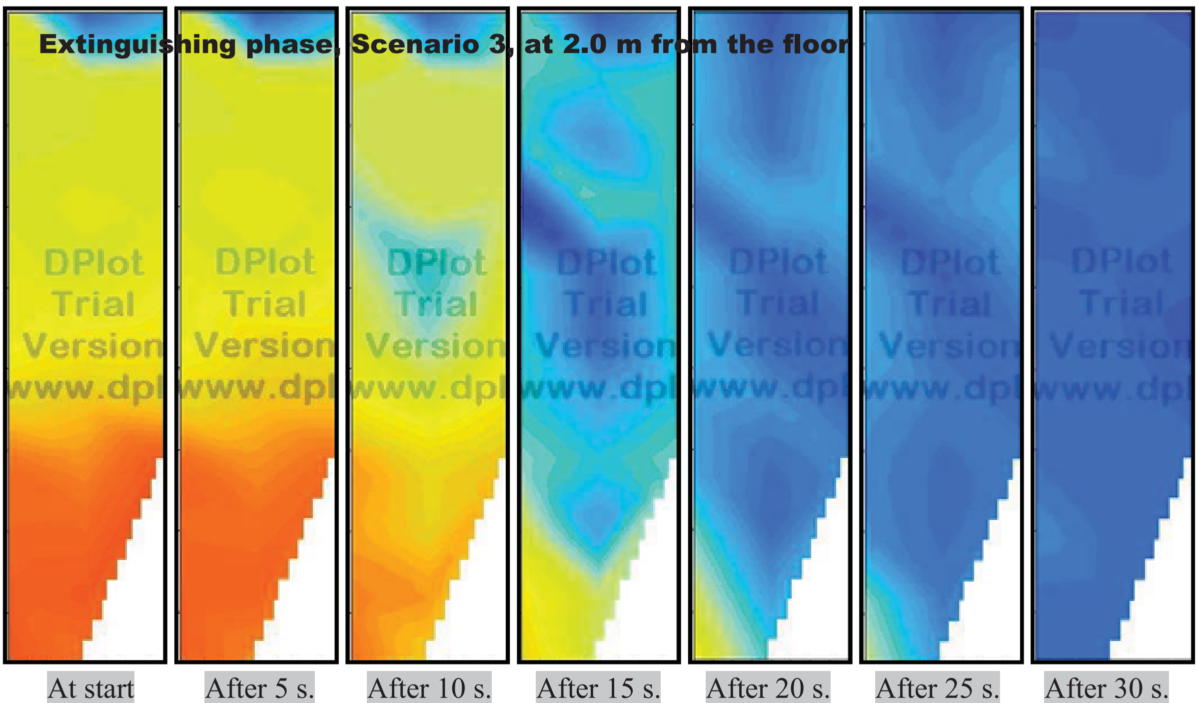
In fact, we observe that it is not the case at all, and even quite the contrary. Indeed, thanks to the extending instrumentation of the compartment with several measuring apparatus, it is possible to support the finding of an under pressure with three different recording medium.

Video record

As detailed in the **Appendice A3**, the cameras placed in the compartment during extinguishing, both on Scenario 1 and 3, were showing a progressive brightening of their screen as soon as water mist has been introduced in the compartment. If it would have been subjected to an overpressure, no clarification would have been possible, since smoke, steam and other gases would have maintained an opaque atmosphere, preventing the daylight to penetrate in the enclosure. Whereas in our case, the screen gradually turns from a complete dark vision to a sort of half light, meaning that the outside air is sucked in, and creates by this way a larger field of vision.
However, this observation remains empirical and impossible to quantify, which would not have been a sufficient explanation if presented alone. But, if the compartment suffers of an under pressure during extinguishing, it means that surrounding air will try to penetrate into the compartment from all the available openings and gaps.
From this assumption, we can take advantage of the Scenario 3, which has the widest openings, to try to see if some planar view could show the entrainment of outdoor air during the extinguishing phase.

Temperature record

Due to the size of the meshing, the widest opening, which involves the entire left door (seen from front wall), is not located in the length of the thermocouples network. We would not see then if a potential cooling is coming from outdoor air, or if it is a phenomenon involving the whole volume near to the front wall.
However, it remains possible to make use of the right window, which has a height from 1.05 to 2.10 m, and a surface of 0.84 m^2. The best solution found for a good visualisation consists in showing horizontal lengthwise slices at the height of 1.2 and 2.0 m.



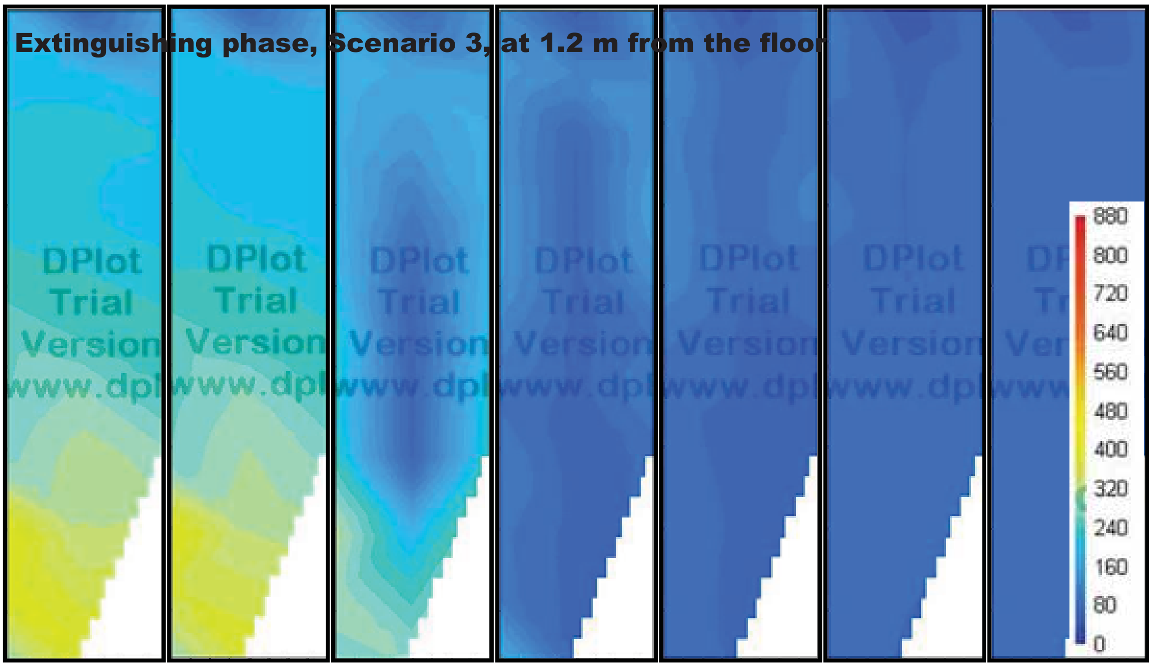


Figure 65. Representation of the temperature evolution during extinguishing, on horizontal planar views, at 1.2 and 2.0 m

At first sight we immediately notice that the slice at 2.0 m seems to be of the most interest, since it shows greater temperature (and then colours) variations. The influence of the left door is visible on the top of the slices, by this dark blue bubble. To locate the window, it is positioned on the left of the images, and at 2/3 of their height.
As usual, nothing seems to be visible during the 5 first seconds. By contrasts, after 10 seconds, there is a pocket of fresh air, at approximately 200 °C, slipping into the yellow smoke layer, remaining at a temperature of at least 500 °C. The phenomenon is even more visible on the later screens, from 15 to 25 seconds, showing an air vein, colder than 50 °C, penetrating in the compartment from this window, and being entrained by the velocity of the water jet passing in the centreline.
The movement of a fluid is always directed by pressure variation, which here led us to think that the compartment is actually entirely under-pressurised, due to crossing streams from one opening to another, since the pockets of outdoor air, in dark blue, are coming from both the window, and from the upper part of the images, where the left door is located.

Pressure records

Finally, the last of our record, and maybe the most telling, is the analysis of the pressure variations in the compartment, thanks to the canes located at 1.05 m and at 2.10 m from the floor and at 6.00 m from the end wall.
The **Appendice A6** is showing the pressure variations for each scenario, during the fire growth and extinguishing phase. And the present graph summarizes all the extinguishing phases of each scenario, but without respecting the start time, to avoid overlapping.

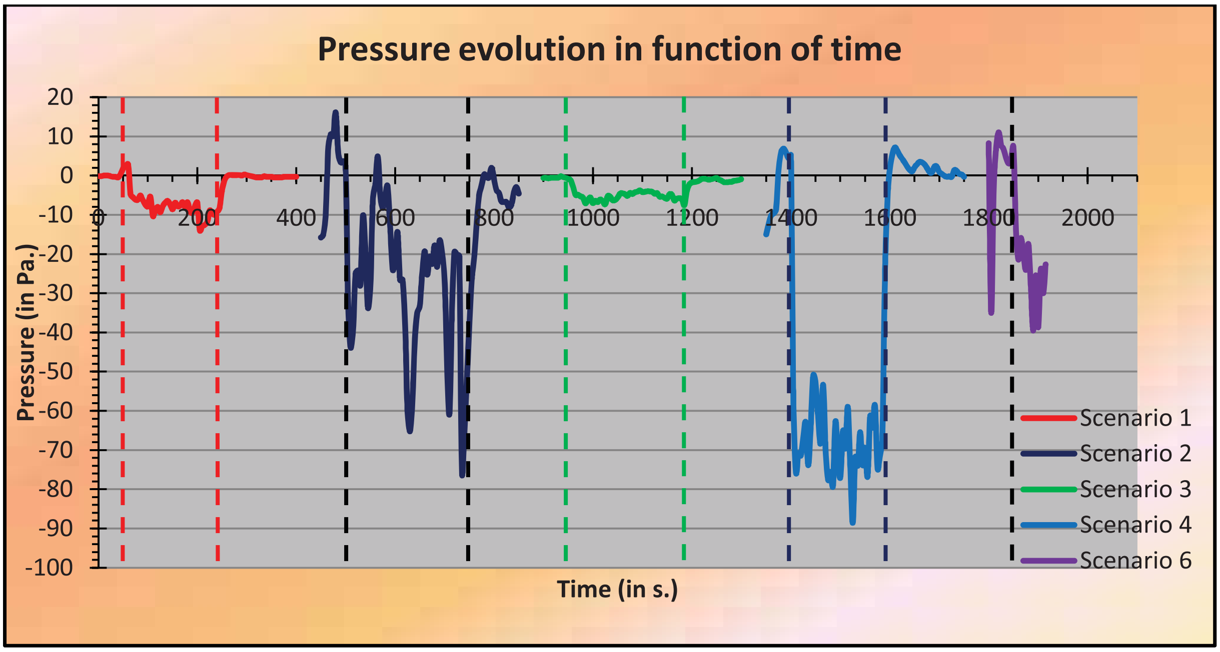


Figure 66. Pressure drops consecutive to introduction of water mist in the compartment. The spraying time is between the dotted lines

The graphs are showing the 50 last seconds before extinguishing, and the whole extinguishing period. We can see that there is a slight sort of overpressure, but smaller than 10 Pa, before a much greater under pressure during all the spraying time.

The values of pressure drops are highly variable, and it seems to not translate to real repeatability, except on the Scenario 3, where it appears normal that the pressure difference is not as high as the others, since it is more easily filled by wider openings.

Even if it is quite surprising to see no attenuation after the gaseous phase has been cooled, it is unlikely to be falsified by Venturi effect on the pressure canes, since they were built with a T junction of the same diameter at the end, and directed vertically. Moreover, the **Appendice A6** compares the measurements done at 1.05 and 2.10 m for Scenario 2, and they show exactly the same curves behaviour, as well as similar values.

Supported by three different observations, there is no doubt anymore concerning the generation of an under pressure when sufficiently fine water mist is used to cool down smoke gases. The risk of a window break due to pressure effect is then quite inexistent, with under pressure lower than 0.7 mBar, as well as concerning life safety for a potential victim (see **Appendice A6**).

The physical phenomenon of under pressure caused by water mist introduction in a warm atmosphere is actually directed by the perfect gas law (or ideal gas law), since:

$$P_0 V_0 = n_0 R T_0$$

Which states that a temperature decrease causes a pressure decrease if the number of moles (n_0) and the volume (V_0) remain constant, or at constant pressure, there is a volume contraction.

Stefan Särdqvist (4), says:

"The fact that water vaporises in the fire room indicates two things. Firstly the smoke will cool because they have used up energy to heat the water. As a result the smoke will reduce in volume. Secondly the volume will increase because of the steam that has been introduced. Which of these two factors predominates depends on where the water vaporises. The energy used to vaporise the water can either be taken from the smoke, or from hot surfaces in the fire room. The energy used to heat the steam further is taken from the smoke.
The amount of energy given off by the smoke is the same as the energy needed to vaporise the water and to heat it to the same temperature as the smoke. We assume that the process happens so quickly that no energy leaves the gases. The system is said to be adiabatic."

As an example, let us show the volume contraction created by heat absorption of water droplets, if 100 % of them are vaporised. The initial smoke temperature is taken at 600 °C, and cooled until 300 °C, whereas steam is heat up from as much.

The equation of change in volume writes it as below:

$$\frac{V_1}{V_0} = \frac{n_1}{n_0}\frac{T_1}{T_0} = \left(\frac{C_{p,g}(T_0 - T_1)}{bM_w L_{v,w} + C_{p,w}(T_1 - 373)} + 1\right)\frac{T_1}{T_0}$$

Which gives with our example:

$$\frac{V_1}{V_0} = \frac{n_1}{n_0}\frac{T_1}{T_0} = \left(\frac{34.0 \times 300}{1 \times 18 \times 2260 + 41.2 \times 300} + 1\right)\frac{573}{873} = 0.79$$

With:

- $C_{p,g}$ *[J/mol.K]* Specific heat capacity of smoke (approximately the same as for air), which is 33.2 at 100 Kelvin
- $C_{p,w}$ *[J/mol.K]* Specific heat capacity of steam, which is 41.2 at 100 Kelvin
- b *[no unit]* Ratio of water vaporised in the smoke
- M_w *[g/mol]* Molecular weight of water, which is 1
- $L_{v,w}$ *[J/g]* Vaporisation heat of water, which is 2260 (or 40.68 kJ/mol)

In our example, the volume of gases (including smoke and steam) is then reduced by a fifth, which would generate an under pressure, since the volume of the enclosure is not compressible.

Särdqvist (4) also add:
"When almost 70% of the water vaporises on hot surfaces and 30 % vaporises in the smoke at 600 °C, the two effect evens out and the gas volume remains constant. Therefore it is sufficient for a relatively small proportion to vaporise in the smoke in order to reduce its volume. In some cases a reduction in smoke volume can cause air to flow into the fire which can increase its intensity"
Replaced now in the context of our experiments, we can state that almost all the water mist is used in the volume, due to a sufficient distance before break up point. This allows production of small enough droplets to follow air streams without hitting the boundaries, and vaporise in their entirety in the smoke volume, causing the contraction of gases, and the following under pressure generated.

Conclusions

Without considering the ability of the Cutting Extinguisher to pierce, drill or cut any type of structural member, this study highlighted a number of characteristics and properties of the produced water mist; concerning both the parametric definitions of the water mist and its fire suppression capabilities.

It was found that the Cutting Extinguisher has an initial velocity of 233 m/s at the mouthpiece, shaping the pattern of the mist into a conical spray having an inner core of continuous water vein, surrounded by an outer ring of very fine mist. The outer cone formed has an angle of 4.5 degrees. This configuration changes at 5 metres from the mouthpiece, distance at which the inner core completely splits up into small droplets and the entrained air. The cross sectional shape of the spray remains circular during maximum 2 more metres after the break up point. The new angle formed by the wider cone from 5 to 7 metres has a radius of 9 degrees from centreline. After 7 metres, there is no more cohesion, and the water mist expands freely in the involved volume.

Considering the studied compartment, we observed undoubtedly the water mist as behaving like a gas would react, meaning by this it can be considered as a total flooding agent. The time required at ambient temperature, to fill the entirety of the compartment was measured as taking less than 3 seconds, which allowed us to deduce an average water content per unit volume of 44 g/m^3. Whether if the water mist is projected into a sealed enclosure, or if there are some openings (2.71 m^2 of open area), seems not to influence drastically the behaviour and pattern of the spray.

According to the visual observations, and video recording, it was possible to deduce a main continuous flow of the mist volume in the involved compartment, starting by travelling from the projection point to the bottom wall, before coming back in the lower half of the compartment's height, and being re-entrained in the outer ring of the jet.

With the collected information about water mist characteristics and behaviour at ambient room temperature, and the multiple instrumentation of the compartment during the burning scenarios, it was possible to deduce some tendencies which could be taken as general rules when extinguishing compartment fires with the water mist of the Cutting Extinguisher.
Even without the benefits of the knowledge of droplet characteristics and size, it appeared that they were at least small enough to achieve some vaporisation yields close to 100 %; meaning by this an extinguishing ability of the water used through the major effect the mist on gas cooling, flame blowing and radiation shielding, and minimal results by oxygen depletion and surface cooling.

The studied fire area involved a surface of 12.8 m^2 of chipboard panels, being fully involved by flames. The cooling times until reaching a safe volume (with regard to risk of rapid fire progress) never exceeded 35 seconds; requiring then less than 33 kg of water. The volumetric mist displacement was noted as keeping the organization of the temperature strata, until they progressively disappear by rising of the lower temperature layer.
Concerning the gas mixing and visibility, it was stated that the introduction of water mist does not really worsen the situation of visibility; neither does it disturb the presence of the lower oxygen layer, allowing the survival of a potential victim during the extinguishing phase.
Still focused on the remaining or improving conditions for a person lying on the floor of the fire compartment, it was found that the radiations were decreased below 2 kW/m^2, which is only twice as

much as an exposure to a sunny day in south of France, and can be sustained during a consequent period of time.

Thanks to the volumetric meshing of the compartment by a hundred thermocouples, we could concentrate on the performance variations of the suppression capabilities of the water mist, with dependence on three parameters, which were the influence of flow rate, fuel surface, and size of the openings. As theory suggested, a reduction of flow rate by half increased consequently the cooling time, but without encountering problems on fire suppression. Indeed, it appeared that the flames were tackled within the very first seconds of water mist introduction, likely to be due to the help of the blowing effect generated by the high velocity of the mist.

As well, the diminution of the variation of the fuel surface causes a variation of cooling time of the same order. For example, the reduced fuel area which has been studied (8.4 m^2) needed only 15 seconds to drop around 100 °C in any region of the compartment. This astonishing ease of extinguishing is certainly due to the smaller heat release rate, but it is also helped by lower initial temperature at fully developed stage of the fire growth (maximum 700 °C instead of 900°C for higher fuel load).

The influence of the openings may have shown the most surprising results, if we trust previous literature. Instead of requiring more time, because of a lower inerting efficiency (by oxygen depletion, lowered by steam expansion), the compartment was cooled much faster. The arguments of sealed compartment for better inerting are true if there is a gas volume expansion, which would dilute the combustible gases and level of oxygen. However, this is not the case, since the yield of the Cutting Extinguisher actually involves volume reduction, and under pressure by the same way. Thus, the openings do not hinder the cooling on the inerting aspect, but facilitate in that way thinner smoke layer and lower initial temperatures, since the combustion gases have a mean of escape.

Finally, it has been observed that the Cutting Extinguisher even after 180 seconds of spraying is not able to prevent a scarce charring material re-ignition. This has no possible comparable fire re-growth than before, but still highlights the necessity of completing the extinguishing by wetting the remaining chars.

The present paper and the data produced during the experiments are of certain benefit for all the users of Cutting Extinguisher, as well as the Civil Swedish Contingencies Agency (MSB), which was always behind the so called Cutting Extinguishing Concept even from the origins. It will be used by the Haut-Rhin Fire Service, in order to be a base of knowledge helping its implementation in the Fire Brigades of the covered territory. More extensively, this study provides information on the volumetric behaviour of water mist within a rectangular shaped enclosure, and provides an evidence of the fire suppression capabilities of water mist.

These experiments were carried out over a period of three weeks, which limited the number of burnings, and the range of measuring instruments. However, it is a first step into the development of volumetric analysis, to understand the behaviour and interactions of the extinguishing medium and the combustion process. Regarding the Cutting Extinguisher, further investigations should be made, especially in determining the diameter and distribution of the droplets. As well, pressure variations and air stream directions should be more deeply studied, in order to better understand the cooling effect, and deduce by this way a predictive method of the most effective way of using the tool.

Finally, we wish this study to be an answer to all questions that may be raised concerning the characteristics and extinguishing ability of the water mist. This work may provide the impulse leading to a generalised use of the Cutting Extinguisher. This could be a revolution for fire fighting, creating the end of unnecessary exposure to the dangerous rapid fire progress phenomenon.

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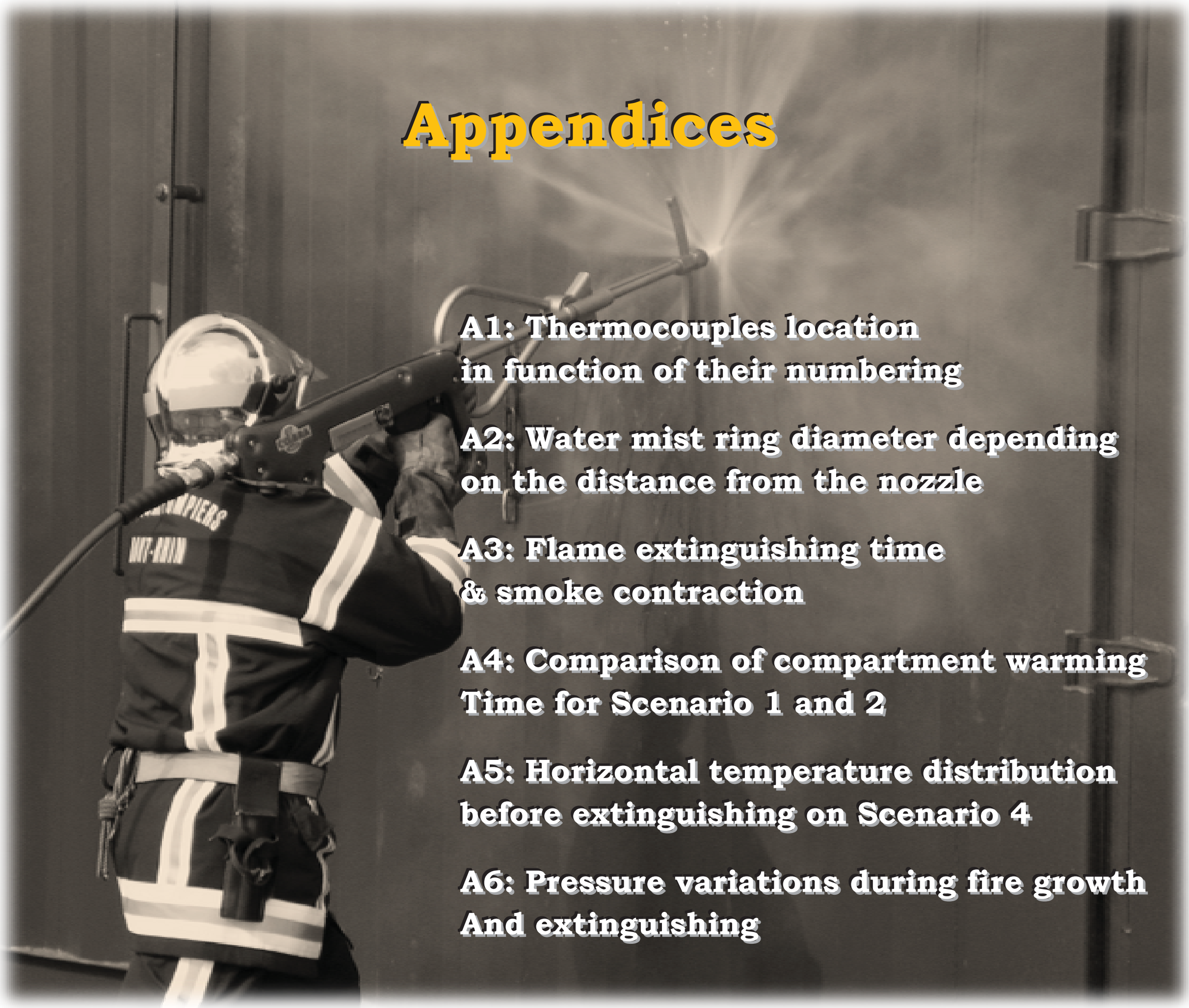

Appendices
A1: Thermocouples location
in function of their numbering
A2: Water mist ring diameter depending
on the distance from the nozzle
A3: Flame extinguishing time
& smoke contraction
A4: Comparison of compartment warming
Time for Scenario 1 and 2
A5: Horizontal temperature distribution
before extinguishing on Scenario 4
A6: Pressure variations during fire growth
And extinguishing

Appendices

A1: Thermocouples location in function of their numbering:

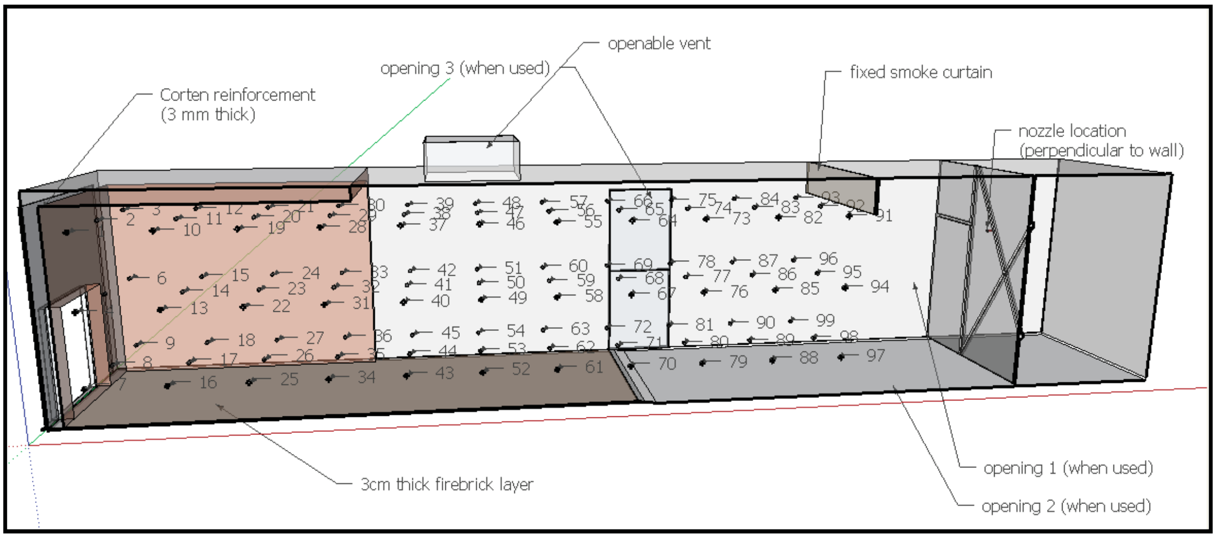


Figure 67. View of the thermocouple numbering from the left face of the compartment

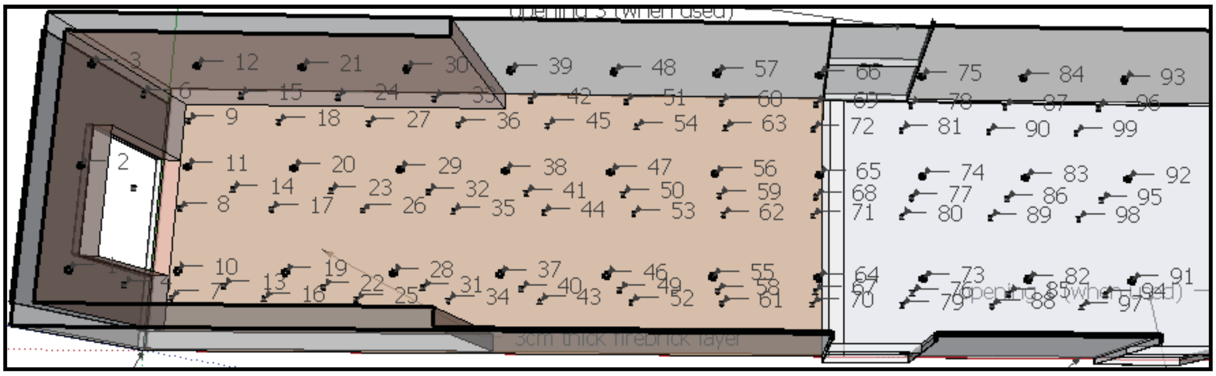


Figure 68. Representation of thermocouple numbering from the top view

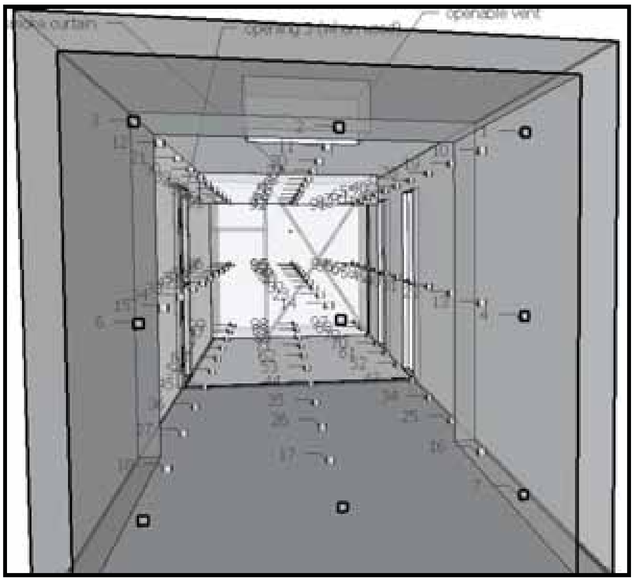
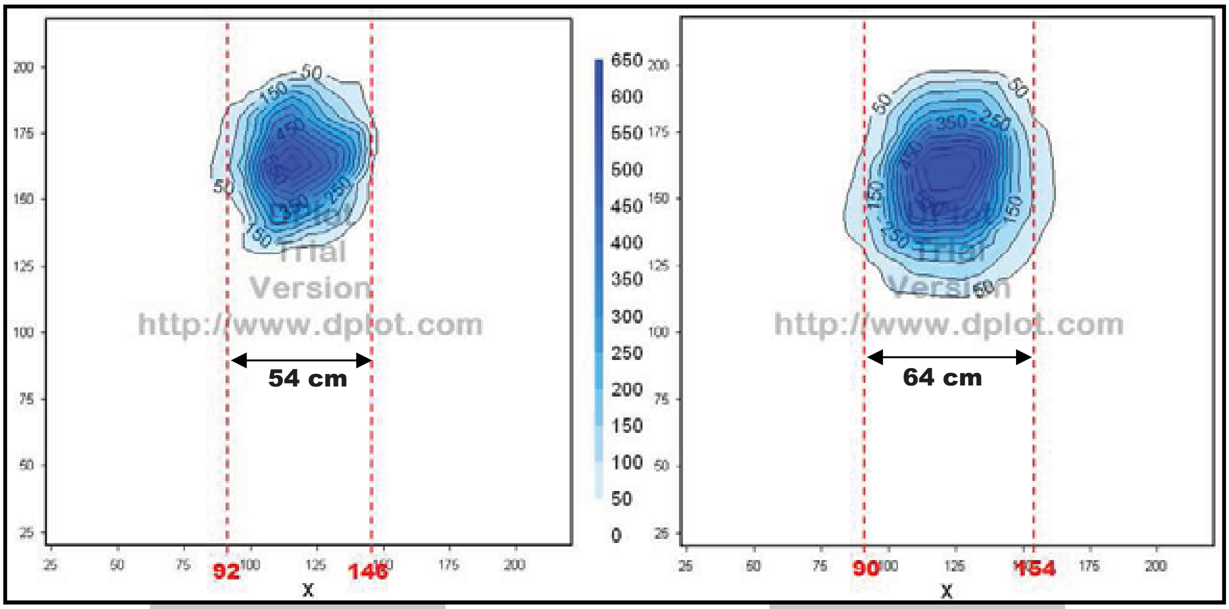


Figure 69. Thermocouple meshing and numbering, seen in depth perception, from the bottom wall

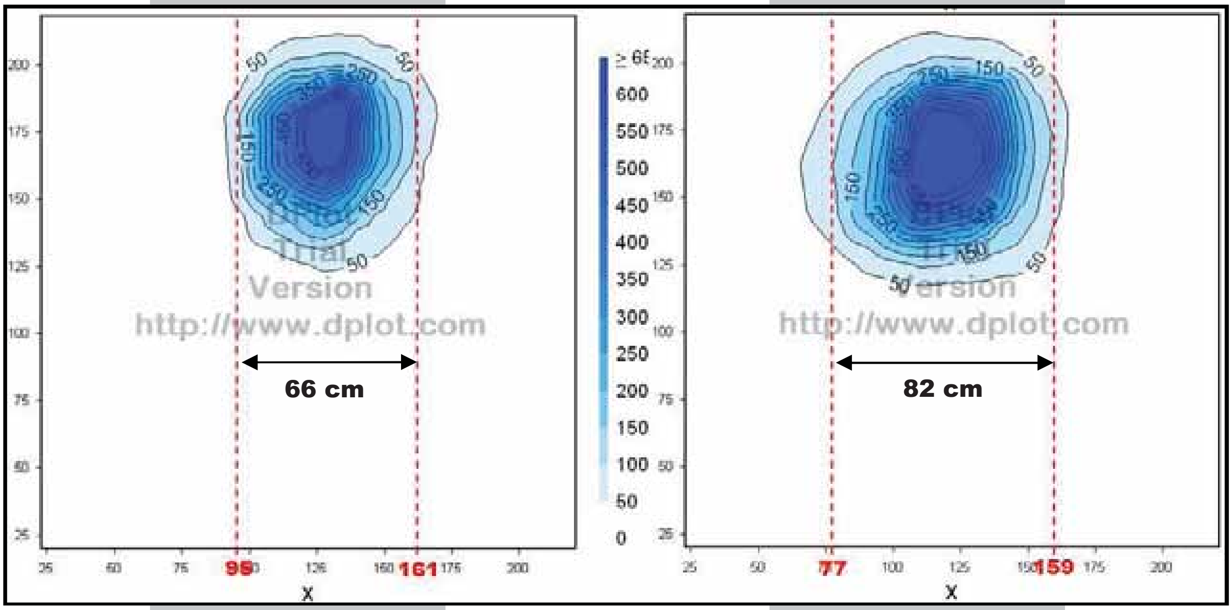
A2: Water mist ring diameter depending on the distance from the nozzle

Taking as reference the ISO surface representing a flow rate per unit area of 100 mL/s.m^2.



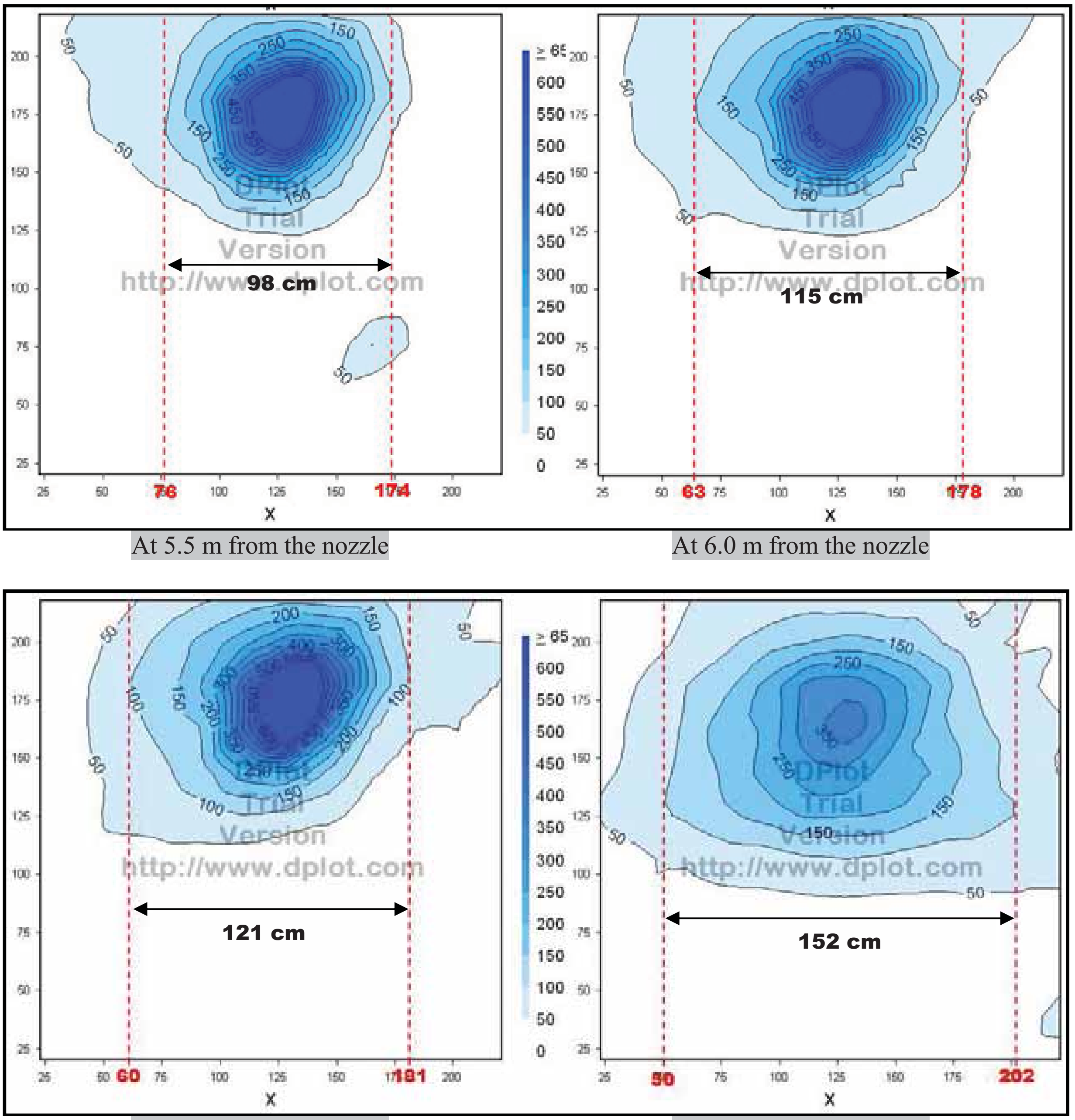
At 3.5 m from the nozzle

At 4.0 m from the nozzle



At 4.5 m from the nozzle

At 5.0 m from the nozzle



At 5.5 m from the nozzle

At 6.0 m from the nozzle

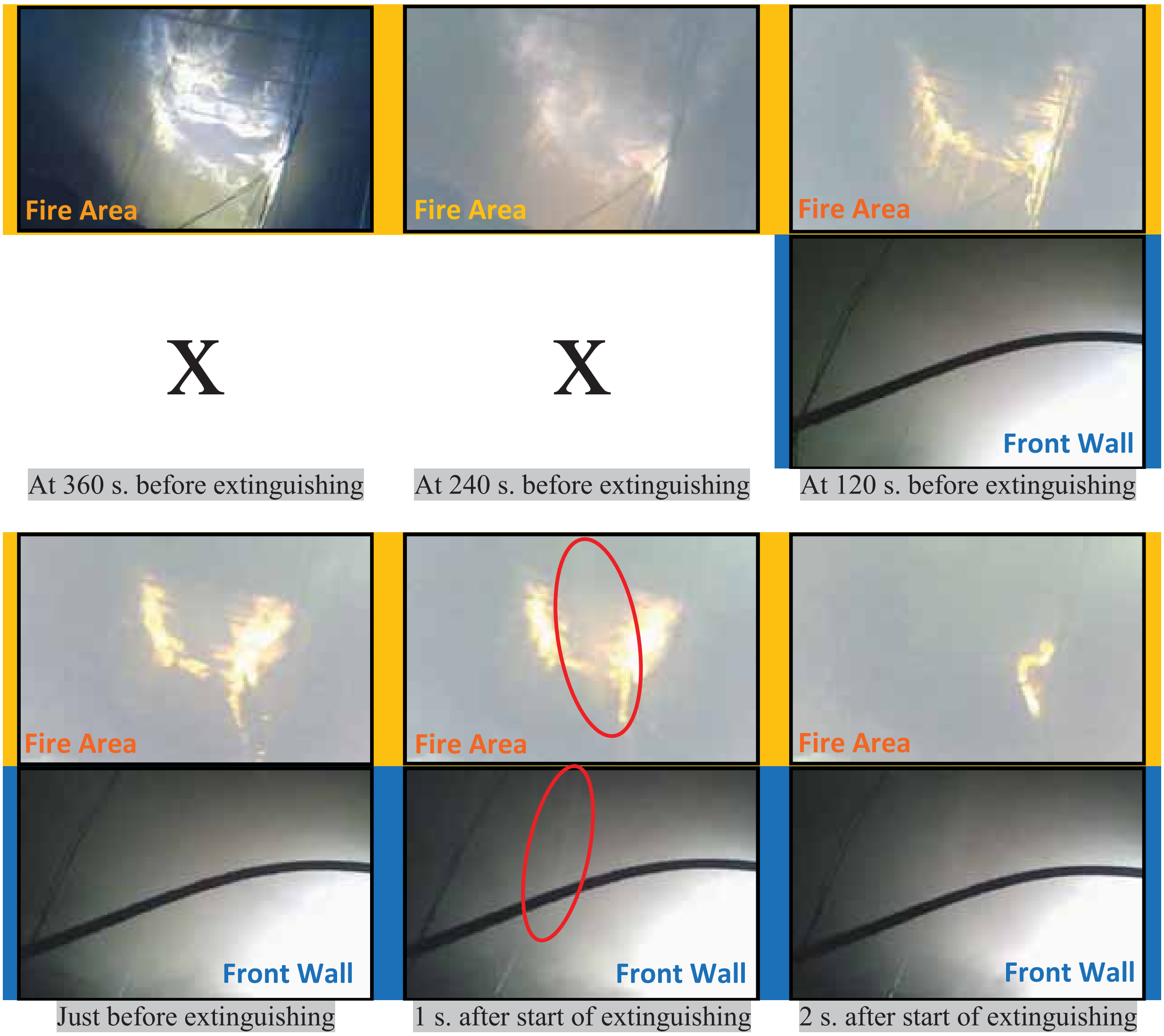
At 6.5 m from the nozzle

At 7.0 m from the nozzle

Figure 70. Perpendicular slices showing cross sectional view of water flow rate per unit area, at several distances from the nozzle

A3: Flame extinguishing time & smoke contraction

As explained in the Results section concerning the full scale burnings, there were several scenarios carried out; each of them showing some variation with the reference scenario. The Scenario number 3 was done with openings in the compartment. Seizing the opportunity of a sufficient brightness in the compartment, we installed two small video cameras. Their position is shown in the chapter dealing with the compartment instrumentation, namely with one targeting the fire area (position 2), while the other is catching the front wall at the same time (position 3, where the mist is introduced).
Some snapshots were taken before the beginning of extinguishing, and with special attention during the water mist penetration. The pictures with yellow background are from the camera at position 2 (Fire Area) and the ones with a blue background are showing the position 3 (Front Wall).



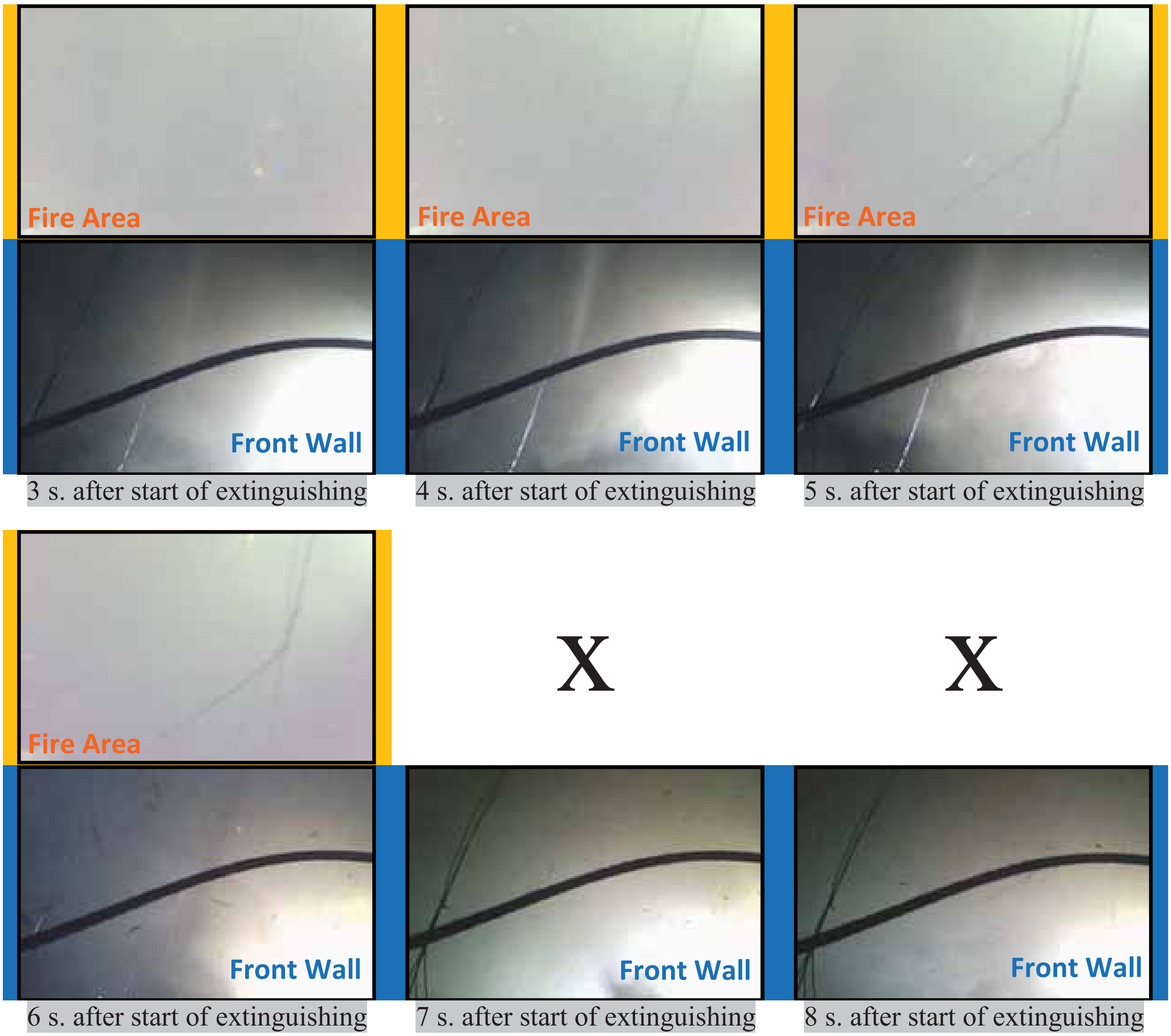


Figure 71. Snapshots taken by the cameras 2 and 3 at several times before and during extinguishing, on the burning Scenario 3

By looking carefully at the pictures, within the 9 last minutes (360 seconds) before start of extinguishing, we can see the view (showing the fire area) getting gradually veiled by the descending smoke layer. This was not noticeable 6 minutes earlier because of the opening of the smoke vent some few seconds before.

Just before beginning the spraying, most of the upper fire area is involved in flames, even if they do not look as virulent as before. Light is diffused and it is impossible to see any details, due to a too thick smoke layer. The opposite view is a bit clearer, due thanks to the open door bringing light from the right. By the way, we can see a TC wire running upward and another one crossing the screen.

1 second after start of spraying, the jet is visible on both views (highlighted by the red markers), but without any other change. 2 seconds after; the flame is reduced to a unique small banner of flames on the right, while the opacity remains the same. At 3 seconds it is not more significant than a spark; and 4 seconds after start there is no flame anymore.

However, regarding the density of the smoke volume, some radical changes are appearing: the smoke cloud seems to lift, and allows some details to be noticeable: at 5 seconds for example, we can see a TC wire and the second opening bringing brightness on the top right corner of camera 2; and the water jet, the TC wire and the gap between the front door and its frame are very noticeable. A space was created and has been filled by clean atmosphere that increases the limit of visibility.

And the last step of evolution, after 6 seconds, smoke is disturbed, betraying the arrival of water mist on the front wall again. No water droplets are visible, but the projection of ash and charring pieces reveals some strong eddies, which calm down immediately, and allows us to see more details than ever, like the TC wire on the pictures taken 7 and 8 seconds after the beginning of spraying.

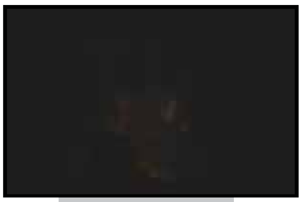
➔ The analysis of the video records allows us to learn some important information:

- On the flame tackling; faster than 4 seconds in this case, which means that the flames are already suppressed, even though no temperature drop is visible at that time. This leads us to establish the supposition that the flames are extinguished mostly by flame blowing and heat extraction in the flame. Assuming the velocity remaining more or less equal, regardless if there is fire or not, we get a filling time of 3 seconds (See the chapter Characteristics of Water mist Cold sprayed for details). The fact that water mist only arrives after 6 seconds to the front wall, when the compartment is involved by fire means that the first 3seconds were entirely used in the fire area and it is only the 3 following seconds of spraying which l enable the compartment to fill.

  Since no thermocouple shows any temperature evolution for a few seconds, causing a plateau (5 to 15 seconds) on the fire curves established in the results section, we can deduce by this that the time of status quo of the temperatures is the maximum time needed for flame suppression (If we devote this level of 5-15 seconds of temperature stability to the flame blowing).
  From this assumption, we take the worst case scenario (number 1), having a plateau of 15 seconds, and deduce the mist quantity used to suppress the fire, which is a maximum 14 kg of water ($flow\ rate \times extinguishing\ time = 933 \times 15 = 14000\ g$). All our fires were then tackled within less than 15 seconds, and using not more than 14 kg of water, in the worst situation.

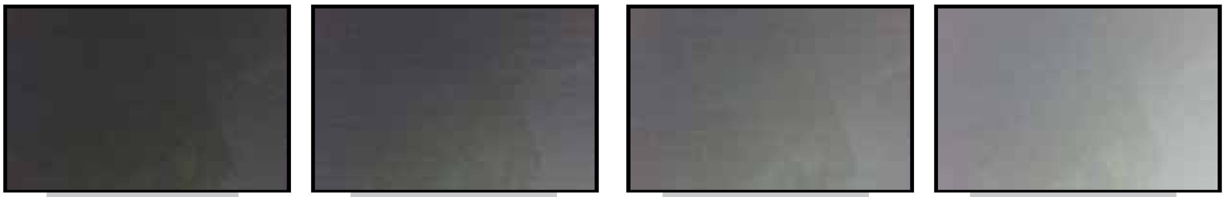
- On the smoke contraction phenomenon. It appears, by looking at the pictures, that as soon as water mist penetrated the compartment, the cameras were subjected to an improvement in their field of vision. This was due to an income air from the openings. Air and all sorts of fluids are moving thanks to pressure variations. Having air penetration in the compartment means that the introduction and evaporation of water mist is generating under-pressure. In order to show that it is not just a stream due to eddies, we also used the only other video record, taken during Scenario 1 (so without openings) from position 4.


At 70 s. before extinguishing


At 60 s. before extinguishing


At 50 s. before extinguishing


Just before extinguishing



6 s. after start of extinguishing | 15 s. after start of extinguishing | 30 s. after start of extinguishing | 60 s. after start of extinguishing

Figure 72. Snapshots taken by the camera 4 at several times before and during extinguishing, on the burning Scenario number 1

The present scenario was then carried out without openings, causing a complete black screen with the descent of the smoke layer. The camera is positioned just in the gap below the front wall, where the Cutting Extinguisher will spray its water mist. Just before extinguishing, nothing is visible, which means that the compartment is completely involved by smoke, from ceiling to floor.

After 6 seconds; time found as being the one required to achieve the initial complete filling by water mist, we can already see a clarification of the screen, which was not the case just before. The process then amplifies until at 60 seconds, a picture showing a greyish atmosphere, which allows some daylight to penetrate. This clarification is due to the fact that air penetrates in the compartment through the wall and door gap, and creates a smoke free space, which is not as opaque to light as smoke, and allows the camera to film on a larger field of vision.

By reversing the explanations, we find the process leading to that phenomenon:

The water mist, which is composed of droplets and entrained smoke, is evaporating, creating steam of course, but also contracting the surrounding smoke and gases, by cooling. The balance of this volume creation and contraction is negative, generating an under- pressure. This sort of “vacuum” is then filled by incoming air from all the gaps in the compartment.

A4: comparison of compartment warming time for Scenario 1 and 2

As mentioned in the **Results** section, dealing with single point's analysis, it appeared that the cooling phase of the compartment could be divided into two parts; the first temperature drop, until approximately 150 °C, and the second one, from 150 until below 100 °C.
The first Scenario was having quite a hard start and a slow temperature drop at the beginning of spraying (35 °C loss per second), compared to Scenario 2 (43 °C per second), but the slip under 100 °C was managed within 95 seconds, whereas the scenario 2 required more than 150 seconds to reach this limit.
The lack of concordance might find its explanation by the differences of remaining warm time of the compartment. Indeed, by measuring the temperature evolution on TC 14 (middle of the height, and in the centre of the fire area), it appears that the time delta between flashover and extinguishing is 155 seconds (2.58 minutes) for Scenario 1, and 405 seconds (6.75 minutes) for Scenario 2. Knowing the type of internal lining of the compartment, which is composed of steel and fire bricks, and the equality of combustible load in both scenarios, we can deduce the following explanations of the differences between both scenarios, regarding to the two cooling phases observed:

- The Scenario 1 faces a situation of fully developed fire, but for only 2.6 minutes. The chipboard is still hanging on the walls, and is sustaining a strong flaming environment. When water mist is introduced, it has to tackle a consequent fire surface, caused by a slower cool down in terms of drops in degrees per second.
  However, due to a short boundary heating time, they did not have time to store so much heat. The second phase, which actually is not representative of the volume cooling, but more on temperature decrease of the walls, does not take too long time, as they were not so hot.

- The Scenario 2 is no longer a fully developed fire, after 6.7 minutes, but the surrounding boundaries are still as hot as if they were in presence of flames. The chipboard panels are starting to fall down on the floor on each other; the fire area is consequently smaller. The water does not have to face a flaming combustion anymore, but only act in a way of gas phase cooling. The temperature drop slopes are consequently steeper.
  Opposingly, the so called "second phase" of cooling has to deal with walls that were subjected to a long heating period, and did have time to store much more heat. The final lowering of temperature is more laborious than in the first scenario.

Although the evidence for this explanation does not call into question the observations, it is good to keep in mind that differences are only valid for a few positions in the compartment, and are not important regarding the temperatures before extinguishing. Furthermore, subsequent analysis in 2 or 3 dimensions (later in the report; see **Volumetric flooding properties** & **Stratification concerns**) allow tempering the significance of these differences.

A5: Horizontal temperature distribution before extinguishing on Scenario 4

As mentioned in the Results section concerning the heat extraction by temperature cooling, some of the temperatures given by the thermocouples were inexplicable, since some differences of about 100 °C were seen, on a same recording height. Assuming an even distribution per layers, due to the rise of heated gases, the data was astonishing, to say the least.
In order to shed light on these records, two horizontal cross sectional views were built, at 0.4 m and 2.0 m from the floor:

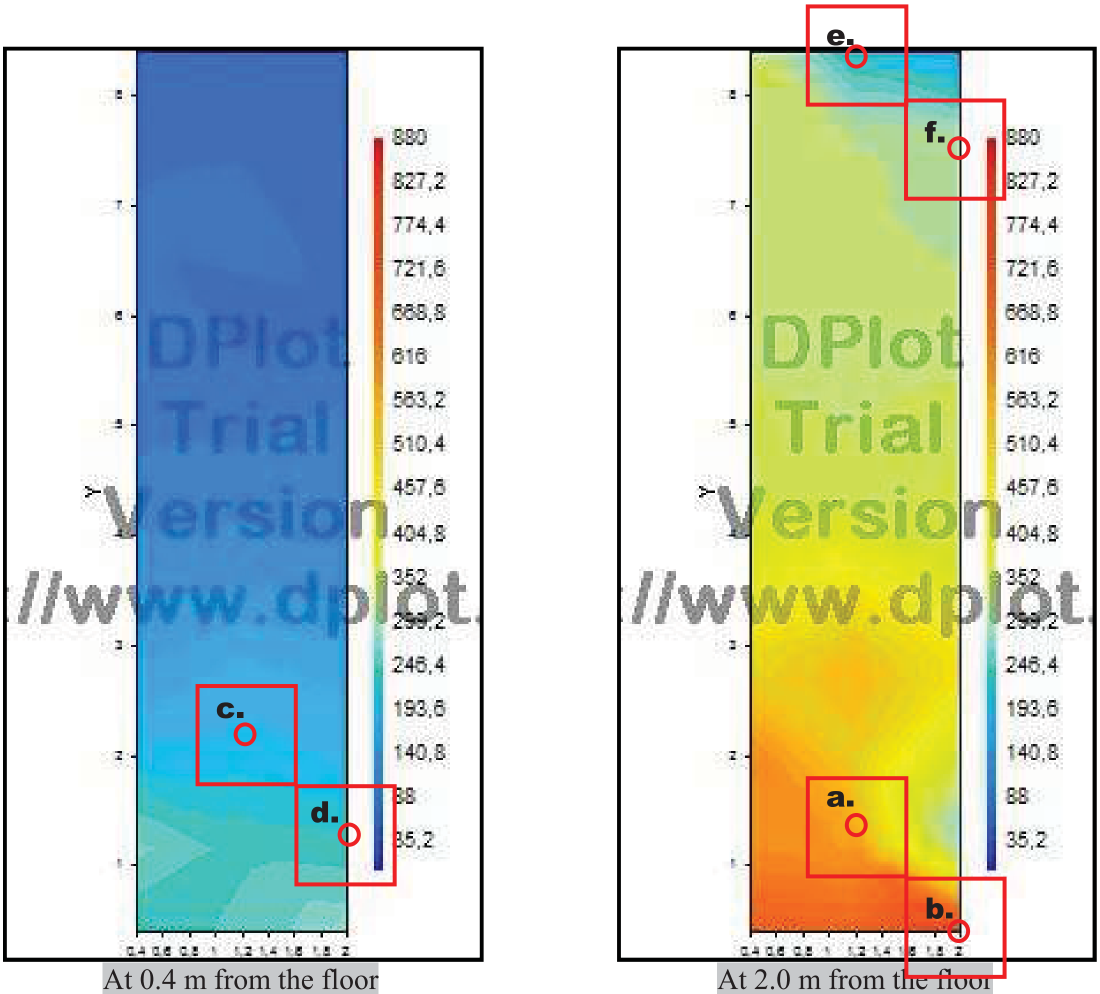


Figure 73. Planar horizontal views of the last temperature record before extinguishing, for the Scenario number 4

Scenario 4 ($Q + S_r + A_c$)	Times are in s							
Position	a.	b.	c.	d.	e.	f.	g.	h.
Last T° record before extinguishing (at 1670 s)	574	673	203	272	216	322	76	80

Actually, the main responsible phenomenon responsible of this disorder is the shape of the combustible arrangement: Since the reduced combustible scenario consisted in removing one chipboard panel on the left (right on the pictures) and one on the ceiling, we got an uneven temperature repartition, especially in the fire zone. As an example, it is clearly visible that the TC at position b. is closer to the combustible, than the one at position a., and the same scheme is visible for positions e. and f.

The consequences of an asymmetrical combustible loading are transmitted on all the compartment length, repeating a triangular configuration, where the right wall (left on the figures) is warmer, on a longer distance than on the left wall (right on the figures).
Less visible when closer to the floor, the same process is happening yet, as we can see on the slice that position d. is on a brighter blue surface (between 246 and 299 °C on the scale) than position c. (between 194 and 246 °C on the scale)

A6: Pressure variations during fire growth and extinguishing

Here are presented all the pressure measurement records thanks to the main data logger. The location of the pressure cane was at 6.0 m from the end wall, 1.05 m high, and 0.4 m from left wall.

- **Scenario 1: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)**

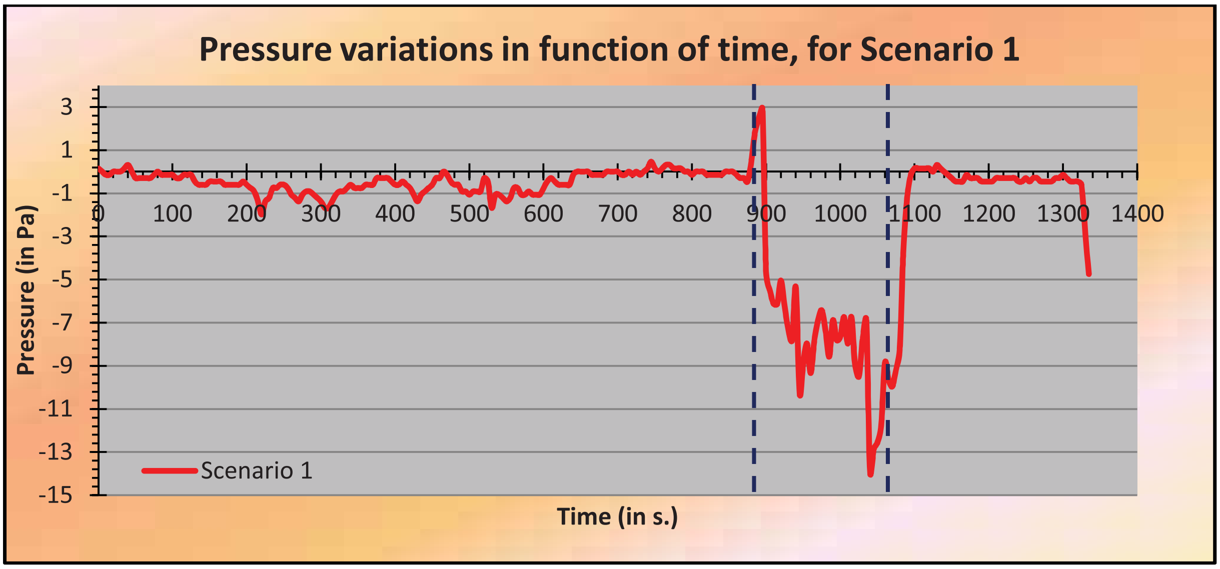


Figure 74. Pressure variations in function of time for Scenario 1

- **Scenario 2: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)**

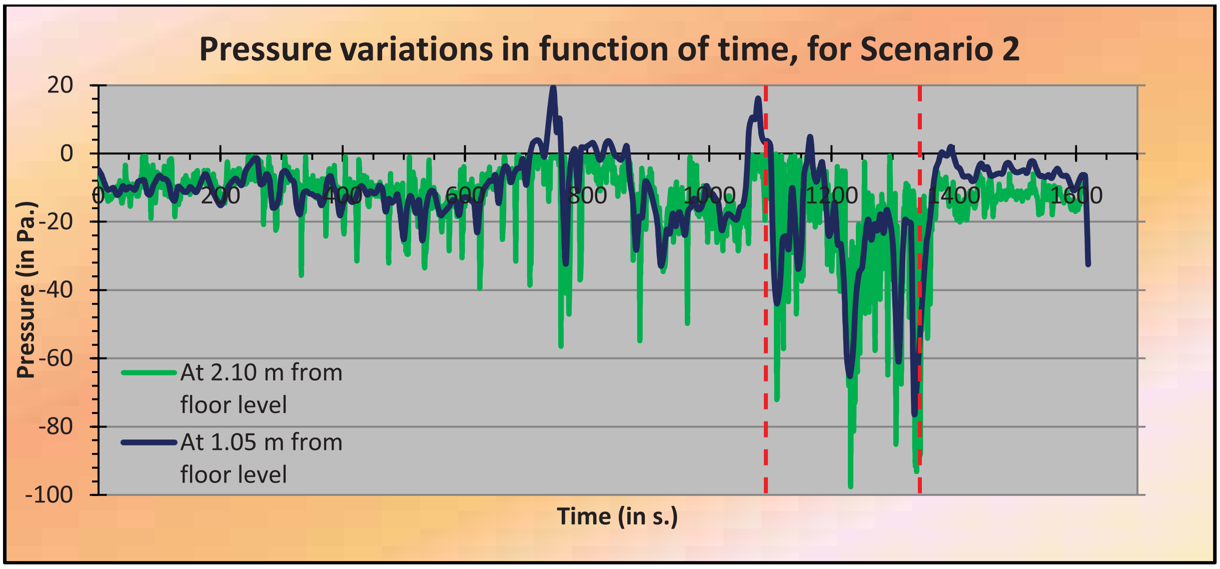


Figure 75. Pressure variations in function of time for Scenario 2

The Scenario 2 (at 2.10 m form floor level) provides a reference of the qualitative behaviour of the pressure variations. Since the additional pressure transducer was manufactured to measure only under pressure, the top of the oscillations going over zero level are truncated. However, all the oscillations are still exactly reproducing the reference pressure transducer at 1.05 m from floor level, and even overlapping the curves for most of the parts. The frequency of the oscillations is higher on the green curve, since the scanning period was only from 1 second, instead of 5 second for the one used as a reference (in dark blue).

- **Scenario 3: Cutting Extinguisher at normal flow rate (56 L/min), full combustible load (12.8 m²) and with openings (2.71 m²).**

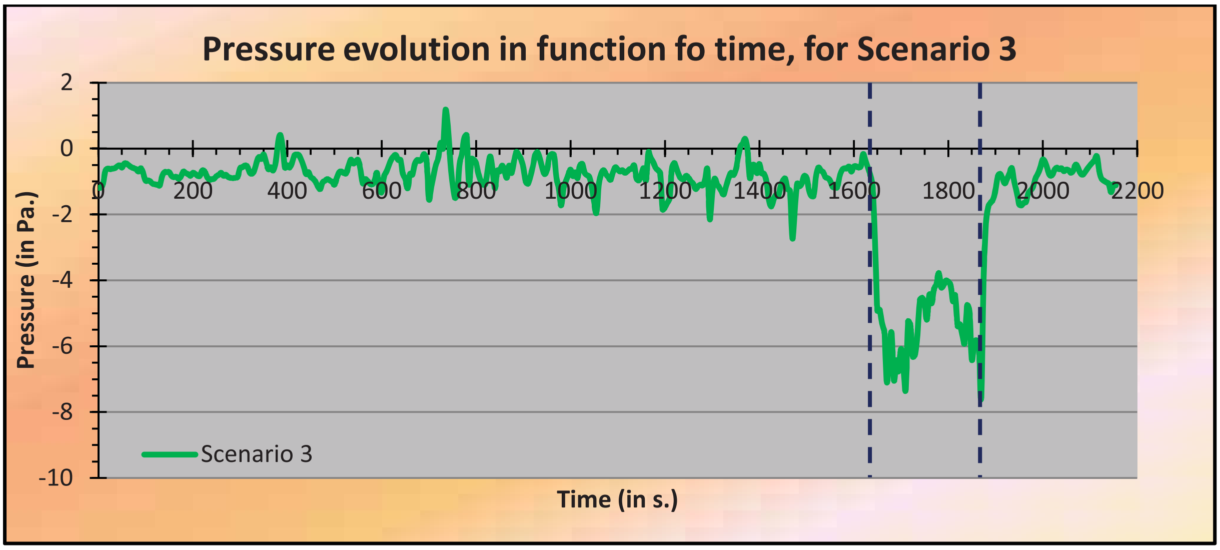


Figure 76. Pressure variations in function of time for Scenario 3

- **Scenario 4: Cutting Extinguisher at normal flow rate (56 L/min), reduced combustible load (8.4 m²) and no openings (0.192 m²).**

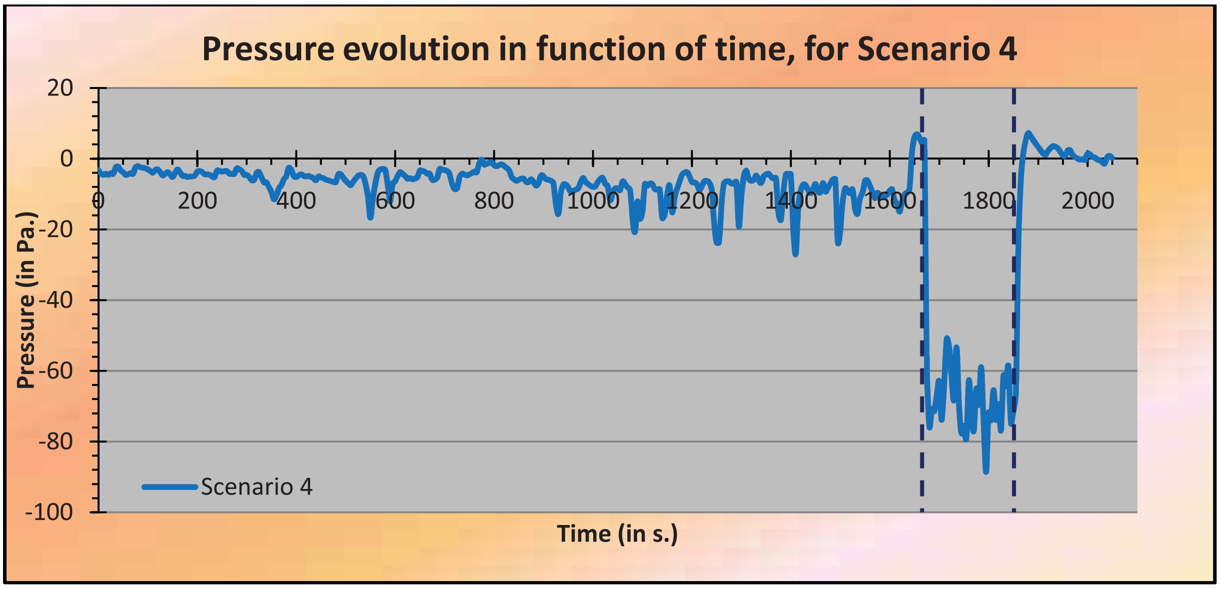


Figure 77. Pressure variations in function of time for Scenario 4.

- **Scenario 6: Cutting Extinguisher at reduced flow rate (28 L/min), full combustible load (12.8 m^2) and no openings (0.192 m^2)**

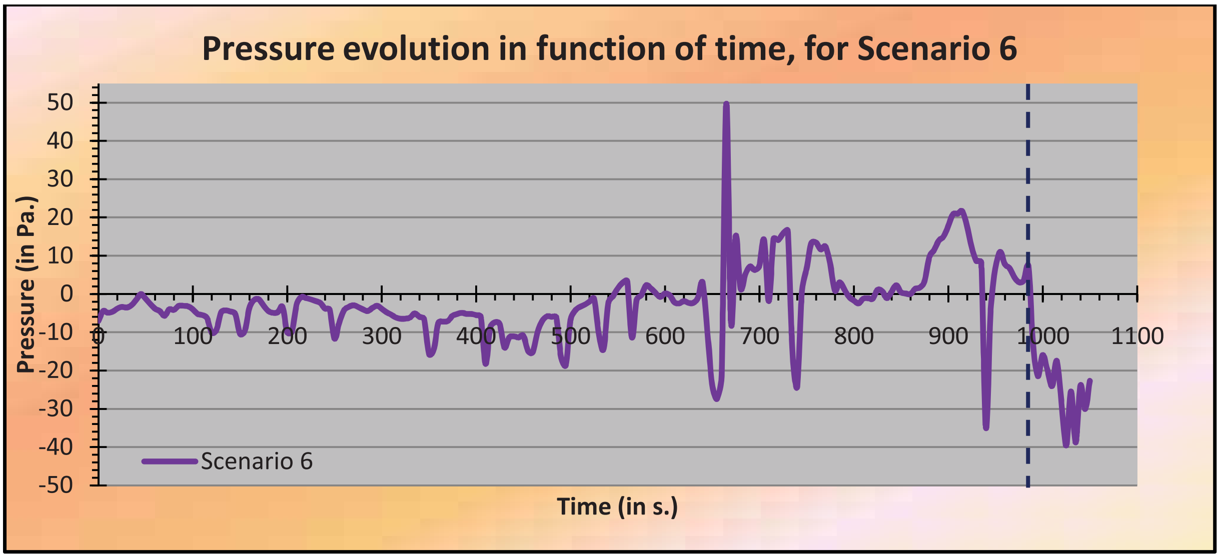


Figure 78. Pressure variations in function of time for Scenario 6

→ At first sight it appears very difficult to use the data on a quantitative analysis. However, on a qualitative point of view, it clearly appears that the water mist projected in the compartment generates a small under-pressure. It is likely for this pressure effect to involve the entire compartment, and not only the pressure cane and hose, due to Venturi effect from the jet stream passing across it, since we notice a significant difference of the drop when the leakage paths of 0.192 m^2 when the compartment is closed (giving values of several tens of Pascal), or if there are openings (in the Scenario 3, having an area of 2.71 m^2, which does not encounter greater difference than 7 Pascal decrease), whether the air streams, and the jet velocity is quite unaffected when the scenario changes.
This can be explained by the facilitated air penetration due to wide openings, compared to the scenarios having only the gaps to fill the vacuum generation by gas contraction.

Concerning the values obtained, should it be due to under-pressure by contraction, or any other phenomenon, we can be relieved concerning a risk of window pane break down. The deepest peak showed a delta smaller than 100 Pa, which can be withheld by all sort of glazed opening.
For human safety, the risk to health is negligible, since the pressure drop is not instantaneous, and the victims are surrounded by the under- pressure; which means that there is no delta between the inner pressure (in the lung) and external pressure.

De feu et de glace…