Backdraft: fire science and firefighting, a literature review

Karel Lambert

Paper submitted in the Erasmus Mundus Study Programme
International Master of Science in Fire Safety Engineering
Course: Explosions and industrial fire safety
Prof. Dr. Ir. Filip Verplaetsen

Contents

Abreviations

CFBT	Compartment fire behavior training
CFVF	Critical fuel volume fraction
DRA	Dynamic risk assessment
FGI	Fire gas ignition
IC	Incident commander
IMFSE	International master of science in fire safety engineering
LFL	Lower flammability limit
LPM	Liters per minute
LODD	Line of duty death
PPA	Positive pressure attack
PPE	Personal protective equipment
PPV	Positive Pressure ventilation
RFP	Rapid fire progress: flashover, backdraft, FGI
SOP	Standard operating procedure
TIC	Thermal imaging camera
UFL	Upper flammability limit

1 Introduction

Backdraft is a fascinating phenomenon. All firefighters have heard about it but it is rarely observed on the fire ground. In firefighting literature it has been the object of a lot of discussions. Backdraft is one type of rapid fire progress. Flashover and fire gas ignition (FGI) are the two other main groups of rapid fire progress. Backdraft has killed several firefighters in the past. It is sudden, unexpected and fierce: "A killer that is waiting around the corner". That is why it is such a popular subject amongst firefighters.

In the academic world there has been a lot of interest in this phenomenon as well. Studies with scale-model experiments and full-scale experiments have been performed in Europe, America, New Zealand and Asia. Research has been done literally all over the world.

The scope of this text is to provide an overview of current knowledge about backdraft. Knowledge from the perspective of the firefighting community and knowledge from the scientific community are brought together. The comparison with other, similar types of rapid fire progress (ventilation induced flashover and smoke explosion), is made. At the end of this paper, an overview is given of possible approaches to deal with this problem from a firefighting perspective.

The author is battalion chief/division chief (Belgian rank: Kapitein) with the Brussels Fire Service and a volunteer firefighter in his home town. He is completing the international master of science in Fire Safety Engineering (IMFSE). His goal is to unite practical and scientific knowledge. This paper is written both for interested firefighters and for scientists who don't have firefighting knowledge. This text should be read in that regard.

2 Backdraft: Fire science

2.1 Definitions

Backdraft is a well-known name in the fire service but it is rather hard to provide a good definition of the phenomenon behind the name. Bolliger [1] states that no comprehensive definition of backdraft exists.

Karlsson & Quintiere [2] provide the following definition:

"Limited ventilation during an enclosure fire can lead to the production of large amounts of unburned gases. When an opening is suddenly introduced, the inflowing air may mix with these, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a glowing ember, can ignite this flammable mixture, resulting in an extremely rapid burning of the gases. Expansion due to the heat created by the combustion will expel the burning gases out through the opening and cause a fireball outside the enclosure."

This is a quite long definition. This is because backdraft is a complicated phenomenon. Several factors are important to describe the phenomenon. In section 2.2.1.1, the factors will be studied in more detail.

In the past several other names were used to describe this phenomenon. In the firefighting community most of these names have disappeared. Some of them are now used to describe other phenomena [3]. Two phenomena which are sometimes confused with backdraft are addressed later in this text: ventilation induced flashover and smoke explosion.

2.2 The phenomenon

Backdraft is a phenomenon that occurs during underventilated fires. An underventilated fire is defined as a fire that becomes ventilation controlled before flashover. When a fire starts in a compartment, it will consume oxygen. The fire will produce smoke and heat. Objects in the proximity of the seat of the fire, will start to heat. The solid combustibles will be transformed into pyrolysis gases. The proximity of other combustible objects and the characteristics of the original burning object will have a major influence on the fire spread.

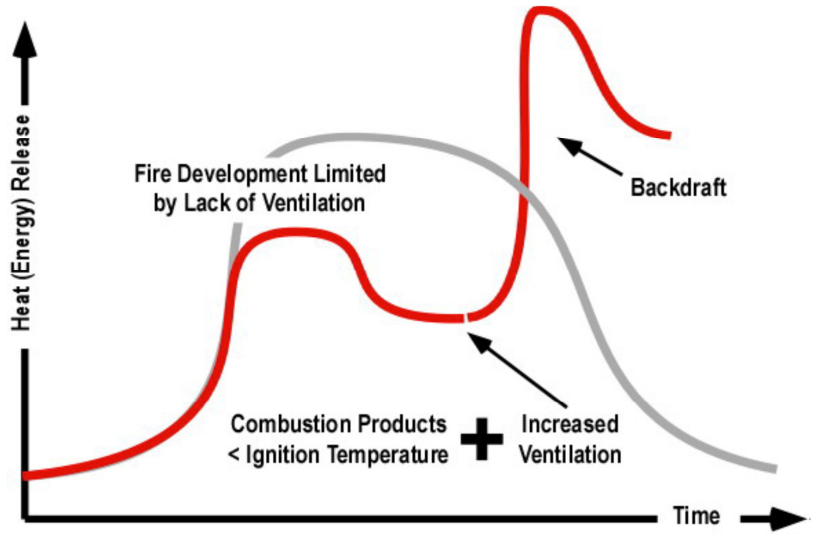

Figure 1 An underventilated fire can lead to backdraft when vented. In that case the heat release rate will peak. *(Figure: Ed Hartin [4])*

When the fire spreads, the heat release rate of the fire will increase. This will cause the oxygen consumption to increase as well. In the case where all windows and doors in the room are shut, the consumption of oxygen will cause a decrease of the oxygen percentage in the room. At a certain point in time the oxygen demand of the fire will become larger than what is available. The fire has become ventilation controlled. The point where the fire makes the transition from the fuel controlled regime to the ventilation controlled regime is called "the FC/VC point". If the transition happens before flashover has occurred, the fire is defined by the fire service as an underventilated fire [5]. In the US, the name "early decay" is also used to address this type of fire.

Due to the heat build-up in the room, pyrolysis will continue. The flaming combustion will cease to exist while the room is filled with unburned pyrolysis products.

When a door is opened or a window breaks, the hot smoke flows out of the upper portion of the opening. Fresh, cold air will rush in through the lower portion of the opening. The resulting current is called a gravity current because of the density difference between the two flows.

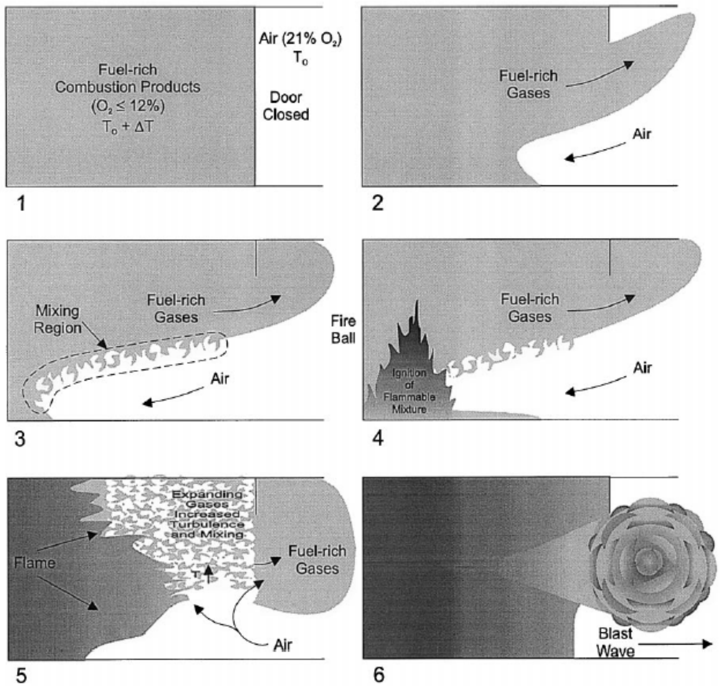

Figure 2 The development of a backdraft *(Graphic: Gottuk et al. [7])*

At the shear layer between the two flows, a flammable mixture is formed. When this flammable mixture meets an ignition source, the mixture is ignited. The flame propagates through the mixture towards the opening. This turbulent combustion creates an overpressure. Smoke and unburned pyrolysis products are pushed through the opening. The turbulence will enhance the mixing of the two flows resulting in a larger quantity of flammable mixture. This is followed by the ignition of the gases outside the room, creating the fireball that is typically associated with backdraft [6]. A representation of this process can be found in Figure 2.

2.2.1 Backdraft vs Ventilation induced flashover

An underventilated fire will not always lead to backdraft when an opening to the room is made. Actually, most of the time, there will be no backdraft. Another event that can follow the opening of compartment in which an underventilated fire is burning, is ventilation induced flashover.

Ventilation induced flashover and backdraft are two phenomena that are very much alike but are not the same. Backdraft is an explosive event that leads to a fireball. Ventilation induced flashover is the result of the continuation of the fire development after the making of the opening. Grimwood [36] describes this difference as a "transient" event (backdraft) and a "step" event (flashover).

When a fire has become ventilation controlled before flashover, the development of that fire is stopped. An image that is used in the fire service is that "someone pushed the pause button of a YouTube video". The fire lacks oxygen to be able to continue its development. When an opening is made, fresh air becomes available. The fire continues its development. The fire will evolve towards flashover as it would have done if it had not become ventilation controlled in the first place. In a normal flashover, the phenomenon is the result of a development from a fuel controlled stage. The ventilation induced flashover is a development from a ventilation controlled stage. The extra ventilation of the compartment induces the flashover. That is why it is called ventilation induced flashover [5]. The difference between the curves in Figure 3 and Figure 1 is very clear. Both are showing a type of rapid fire progress but backdraft is an explosive event while ventilation induced flashover isn't.

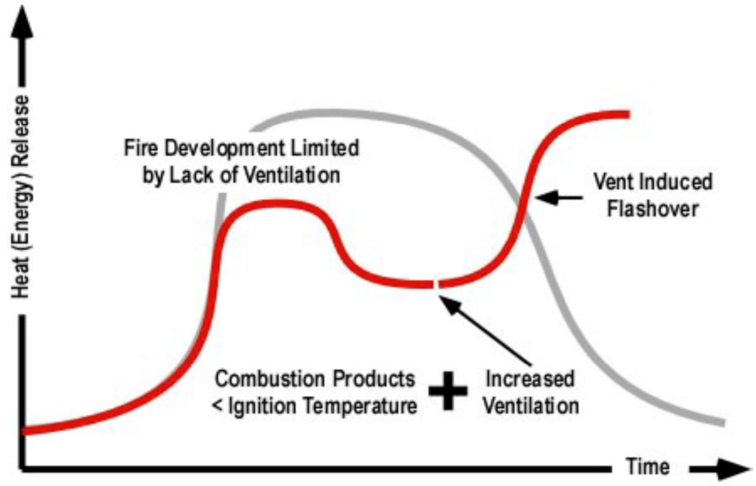

Figure 3 An underventilated fire can also lead to ventilation induced flashover when vented. Notice the difference with Figure 1. *(Figure: Ed Hartin [4])*

Hartin [8] and Gojkovic [6] refer to a gray zone (See Figure 4) that exists between the two curves. Hartin considers the two phenomena as limit states. Both phenomena are possible and appear from time to time on the fire ground. The curves in the zone between the two curves are also possible in reality. Often it will be very difficult or even impossible to determine what kind of phenomenon has been produced on the fire ground. This is because of the grey zone. Phenomena which look like flashover but have a small pressure wave have been reported as are backdraft like phenomena where there is a fire ball but the pressure wave is absent.

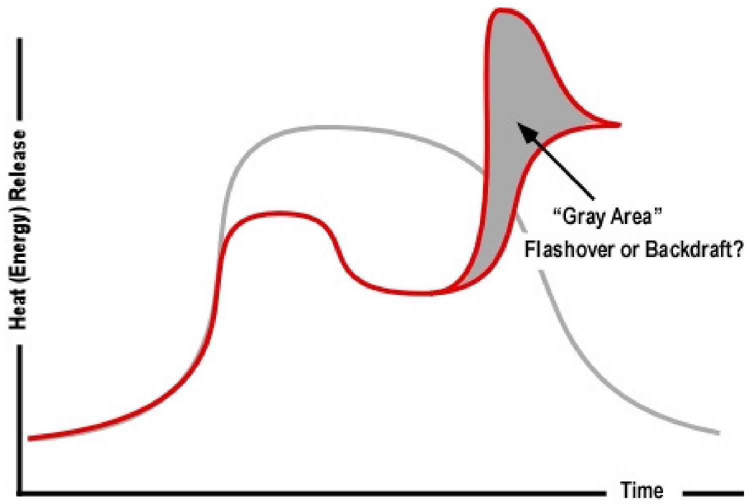

Figure 4 This graphic combines Figure 1 and Figure 3. The gray zone is created between the two curves. Ventilation induced flashover and backdraft are considered to be two limit states. All phenomena between the two curves can take place as well on the fire ground. *(Figure: Ed Hartin [8])*

2.2.1.1 *Ventilation controlled fire/underventilated fire*

A fire that produces a backdraft is always an underventilated fire. The fire needs to have a lack of oxygen to be able to produce large quantities of unburned pyrolyzates. Those are needed to create the conditions for backdraft (See 2.2.1.2). Often these ventilation conditions are present in closed compartments or compartments with a very limited ventilation. After the start of the fire, the oxygen in the room will be consumed. At a certain point in time, the fire will need more oxygen than the room can supply. The burning regime will become ventilation controlled.

Tuomisaari [10] performed 1/4th scale experiments where a door to the fire compartment was opened. The time between the ignition of the fire and the opening of the door was varied. He found that no backdraft occurs when the door is opened too early. In such cases the inflow of air leads to an increase in the burning rate but no flashing flames were observed. In experiments where the door was opened after a longer delay, backdraft did occur. The reason for this can probably be found in the fact that enough unburned pyrolyzates have to be released for backdraft to occur (See 2.2.1.2). When the door was opened after an even longer delay, the seat of the fire could not be reignited and the fire was extinguished. This leads to the conclusion that a situation with a backdraft risk can be handled by keeping the enclosure air-tight. In practice this may not always be possible.

In the fire service, several objects are used to train firefighters in fire behavior. Two of those are used to demonstrate the underventilated fire and backdraft in particular. The "doll's house" (Figure 5) is a small-scale prop constructed of wood. Typically there is a door opening that provides fresh air to the fire. During the demonstration, a fire is lit. When the fire has developed, the door is closed to limit the entry of oxygen. Due to the heat in the doll's house, the wood continues producing pyrolysis gases. When the door is opened afterwards, air rushes in and smoke leaves the compartment through the upper part of the opening. Often a mini backdraft is the result. A window cell (See Figure 6) is a full scale prop to demonstrate backdraft to firefighters. It is constructed of a 20 foot shipping container. A stack of pallets is set on fire in the container. When the stack of pallets is fully developed, the door to the cell is closed. The fire will produce large quantities of unburned pyrolyzates due to a lack of oxygen. After the opening of the door, backdraft is likely to occur.

In both cases, the instructors are demonstrating a sequence of events that are unlikely to happen in reality. They start a fire in a ventilated enclosure. When the fire has become (nearly) fully developed, they close the door to the enclosure and limit the air supply. In reality it is unlikely that the fire service arrives on a fire scene where somebody has closed the door to a fully developed fire. Nowadays, firefighters are taught to close doors to the fire compartment in order to slow down the fire development. This tactic is called anti-ventilation. In such cases it might be possible to recreate the sequence of events as in a doll's house session but the backdrafts that have been reported on the fire ground in the past were probably not caused by a mechanism where the oxygen supply is stopped after the fire has become fully developed.

Both training props are good tools to teach fire behavior but instructors should realize that there is a difference between what they are showing to the students and the backdrafts that are seen at the fireground.

Figure 5 Sequences of a four compartment doll's house demonstration. The fire is fully developed in the upper right compartment in the first picture. Three openings are closed in the second picture. The fourth room doesn't connect with the other rooms. The fire generates lots of pyrolysis gases (picture bottom left). When the doors to the three rooms are opened, a backdraft like phenomenon occurs *(Picture: CFBT-NL)*

This can also be said about the study by Aiping et al [11]. They used a freeburning period to generate sufficient heat for the pyrolysis to start. After this free burning period, the door to the fire room was closed. In reality, it is often the case in underventilated fires that this quantity of heat has to be generated with the oxygen available in the volume. This is a limiting factor. Often there will be not enough oxygen in the room to produce the energy needed to have massive production of pyrolysis gases.

This mechanism offers a tactical possibility for the fire service. When the fire service arrives at a building where there is an underventilated fire or where a backdraft risk is present, it is possible to keep everything closed. By doing so, all the preparations for firefighting can be made when the fire is "paused". This is another way to apply anti-ventilation (See 3.2.3.3). When applying such a tactic, the firefighters must keep in mind that a window failure or a partial collapse will change the conditions drastically. They should be prepared for this.

2.2.1.2 Unburned pyrolyzates

An article by Steward in 1914 is the first appearance of the term backdraft in literature. He describes backdraft as a dust explosion caused by the carbon particles in the smoke [1]. The belief that backdraft is fueled by carbon monoxide has been widespread ever since. Later, several studies show that this is a misconception. Backdraft is fueled by unburned pyrolyzates and not by carbon monoxide.

In experiments, Fleischmann et al [12] found that there needs to be a mass fraction of unburned fuel that is higher than 10% in order to create the conditions for a backdraft. Fleischmann used methane in his tests. The upper flammability limit of methane is well known. Drysdale [13] mentions a volume fraction of 15%. At first sight, this seems contradictory with the findings of Fleischmann because it seems that a value within the flammable range can lead to backdraft. Methane is a very light molecule. A volume fraction of 15% methane in air equals a mass fraction of 9%. With this in mind, the value found by Fleischmann is clearly higher than the upper flammability limit.

In his doctoral thesis [14], Fleischmann writes that the mass fraction of unburned fuel should be higher than 15% for backdraft to occur. It becomes clear that there is a critical value for the mass fraction of unburned fuel but that there is no agreement on the exact value.

Experiments by Gottuk et al. [7] onboard naval ships show that the critical mass fraction is 16% when the fire is fueled by diesel. They find that no backdraft is produced with a mass fraction below 15%. There is a transition region between 15% and 18% where sometimes a backdraft is produced and sometimes there isn't. Above a mass fraction of 18%, backdraft occurs nearly always. Gottuk et al. show that this critical mass fraction decreases if the mass fraction of oxygen in the mixture increases prior to the opening of a door or window. For example a hexane fire is started in a room. If the mass fraction of oxygen in the room reaches 10% in the steady state prior to the opening of a door, the critical mass fraction of fuel will be 6.5% which is a lot lower than the value for an atmosphere with 0% oxygen.

Ivan Bolliger [1] performed full scale tests in New Zealand. His tests were performed with methane as fuel. He finds that the required total unburned hydrocarbon concentration must be higher than 15%. This is the same number as found by Fleischmann in his doctoral thesis [14].

Mao et al [17] did research into the occurrence of backdraft in tunnel fires. Experiments in a 1/8th scale tunnel were performed using heptane as fuel for the fires. They find lower values for the critical mass fraction of the unburned fuel. A critical value of 8.78% is found for the single tube configuration with natural ventilation, while 11.71% is found for the twin tube configuration with mechanical ventilation. They also found that the humidity of the inflowing air is important. A high humidity of the air will prevent backdraft from occurring. The difference between the values of Mao and those found by Fleischmann, Bolliger and Gottuk can be explained by looking at the oxygen mass fraction. The latter has oxygen mass fractions in the order of 10% while Mao has 14.25% in the single tube configuration. A higher oxygen mass fraction leads to a lower critical unburned fuel mass fraction [17],[18].

Bolliger [1] refers to Fleischmann to state that the severity of the backdraft increases with increasing hydrocarbon concentration but didn't find a general trend in his own full-scale experiments. Weng et al [18] confirmed Fleischmann's findings with the results of their 1/4th scale research.

This scientific research teaches us that there is a critical mass fraction of fuel that is necessary for backdraft to occur. Mao et al find that an increased humidity can prevent backdraft. By introducing water in a closed compartment, the humidity will increase. Due to the overpressure a mixture of water vapor and gaseous fuel will leave the compartment. The resulting mixture inside will have a lower fuel mass fraction. The practical application of these findings will be discussed in section 3.2.1.

A first reflection that has to be made is about the fuel that is used during the experiments. Nearly all experiments used methane, heptane or diesel. There is a difference between those and real pyrolysis gases, which are fueling real backdrafts. The reason for this is that gaseous fuel or liquid fuel is easier to control than pyrolysis products. This is necessary to have repeatable conditions. On the other hand, it is interesting to study the differences between the two fuels. In the experiments, it is known how much methane enters the compartment because it is an experimental variable. In reality it is less well known how fast pyrolysis gases are generated. This is an important difference since the mass fraction of the unburned pyrolyzates is the critical factor that determines the occurrence of backdraft. Research into this could bring new insights and increase the understanding.

One study used wood, alongside heptane as a fuel for backdraft experiments: Aiping et al [11] made a theoretical derivation and performed experiments in a box that was 68 cm long, 42 cm wide and 42cm high. They propose to use the ratio between the volume fraction of the fuel and the lower flammability limit. This ratio is indicated with β. The reader is referred to [11] for further reading.

A second reflection that is interesting is the temperature in the room after the FC/VC point (See 2.1). The heat release rate will drop after this point. In the case of the underventilated fire, this can lead to the situation where the fire has become ventilation controlled before sufficient heat for massive pyrolysis has been released. In those cases, no backdraft will occur when an opening is made because the fuel mass fraction is too low. In order to pass the critical fuel mass fraction, there must be enough heat in the room to start the pyrolysis process. Not only must it start, it must also generate sufficient pyrolysis gases to pass the critical value. In passive houses, which are almost airtight, it may be the case that the temperature in the room is too low to generate sufficient pyrolysis.

2.2.1.3 Inrush of air/Gravity current

After a fire has become underventilated, the smoke and pyrolysis gases in the compartment have a temperature that is significantly higher than the outside air. The outside air is colder and heavier than the hot gases inside which are lighter.

When an opening is made, the hot gases flow out of the top of the opening. The heavier gas (air) flows under this hot outflow of fire gases. The bigger the difference in temperature (density) of the gases, the higher the velocity of these two flows. This current, caused by the density difference between the fluids, is called a gravity current.

The zone where these two gas layers meet is called the shear interface. Due to turbulence, parts of the two layers are mixed. A flammable mixture is formed at the shear interface. This flammable mixture propagates into the compartment. It rides on the gravity current as "a surfer on a wave" [15].

Fleischmann [14] describes that this gravity current flows until it reaches the opposite wall. In his experiments, there was an ignition source at the opposite wall. When the flammable mixture meets an ignition source (flame, glowing ember), the mixture is ignited. A front of flames will move towards the opening, through the flammable mixture created by the gravity current. Several researchers looked at the velocity of this gravity current. There is a link between the velocity of the gravity current and the delay between the opening and the occurrence of backdraft. This delay is the time which is needed for the gravity current to travel to the ignition source. This means that the delay equals the distance from the opening to the ignition source divided by the velocity of the gravity current.

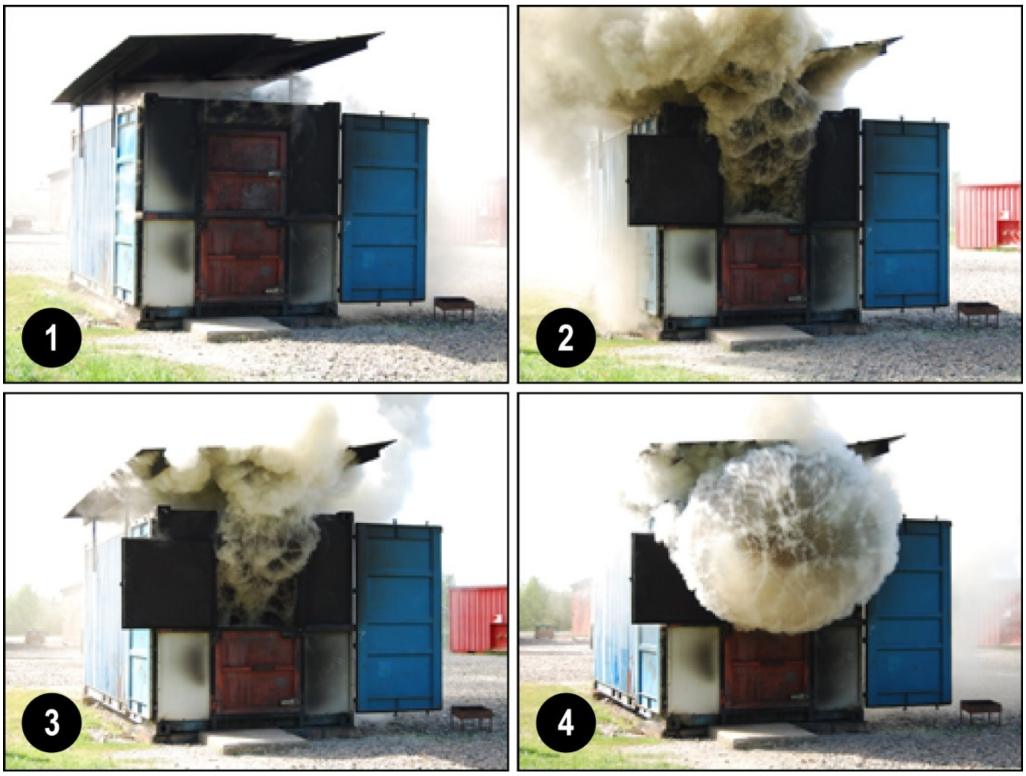

Figure 6 Backdraft demonstration with a Window cell. The first picture shows light colored smoke exiting through gaps. In the second picture, the upper part of the door is opened. A bi-directional flow appears. The upper part of the opening is used as exhaust while fresh air enters through the lower part of the opening. Picture 4 shows the smoke that is pushed through the opening. This picture has been taken between the ignition inside and the appearance of the fireball outside. *(Pictures: Ed Hartin)*

Bolliger [1] reports delay times between the making of the opening and the ignition between 3.0 and 6.3 seconds. This means that the gravity current has a velocity between 0.95 and 2 m/s. Chitty [3] mentions that the delay increases when the volume of the space increases. This is consistent with the findings of Fleischmann.
It is important to notice that the ignition source doesn't have to be at the opposite wall in reality. Other configurations are possible as well. This will have an influence on the delay and the intensity of the backdraft.

A second reflection that has to be made is that most of the research has been done with vertical openings which are simulating doors and windows. When a horizontal opening is made in the roof of a compartment, the flow pattern will be completely different. The presence of a second (vertical) opening, the size of the opening, … will have major influence of the movements of the smoke and air.

Tuomisaari [10] writes in his report about smoke ventilation that no backdraft was ever observed when a ceiling vent was open.

The presence of obstacles in a room will decrease the velocity of the gravity current. Moreover, the obstacles will create more local mixing and turbulence but not necessarily a well-mixed situation in the compartment [16]. This means that the time between the making of an opening and the occurrence of backdraft will be longer in a room with furniture than in an empty room. Due to the increased local mixing, the backdraft can be more intense. For firefighters it is important to realize that the situation is not safe when backdraft has not occurred in the first seconds after a door has been opened. They might get a wrong impression by backdrafts shown to them in training programs. Typically, shipping containers that have been transformed into a so-called "window-cell" are used for backdraft demonstrations (See Figure 6). During these burns, the window cell does not contain any other items except for the stack of pallets that is fuelling the fire. When backdraft occurs in a room with furniture, the intensity of the backdraft will be higher than in an empty room.

Mao et al. [17] found that the humidity of the inflowing air is of importance when researching the occurrence of backdrafts in tunnels. It is found that increased humidity can stop backdraft from occurring even with higher mass fractions of unburned pyrolyzates. Mao remarked as well that there is a difference between a gravity current and the inflow of air caused by mechanical ventilation.

2.2.2 Pressure

2.2.2.1 Pressure evolution in the room prior to backdraft

In the beginning of the fire, the room contains 21% oxygen. When the fire evolves and grows, part of the oxygen is consumed and replaced by combustion gases. Moreover, unburned pyrolysis gases are released into the volume. These hot gases want to expand. This will create an overpressure in the room. Smoke will exit through cracks and openings. It happens that smoke exits through the gaps around the door (See Figure 7).

At a certain moment in time, the heat release rate of the fire will decrease due to a lack of oxygen. The flaming combustion will stop. The production of combustion gases will decrease. When the flames disappear, the radiant heat towards the fuel decreases. This will result in a decrease in production of pyrolysis gases. Smoke will continue to leave the room through cracks until the overpressure drops to zero.

Later in time, the gases in the compartment will start to cool since they lose energy to the boundaries (walls, floor and ceiling) of the compartment. Energy is conducted through the walls and leaves the compartment. The walls will cool the fire gases in the compartment. A decrease in temperature will cause shrinking of the gases. This will result in an relative negative pressure in the compartment. Fresh air will be drawn into the compartment through the cracks that were previously used to evacuate the smoke.

The freshly introduced air contains oxygen. The fire will use this oxygen to increase its intensity. The heat release rate will increase. This will lead to the production of smoke and the pressure in the compartment will start to rise again. The introduction of the fresh air will stop and smoke will start to evacuate through the cracks. Because of a lack of oxygen the heat release rate will decrease. A cyclic process can be started. The room will alternate between overpressure and negative pressure.

Figure 7 Firefighters during an exercise in the backdraft cell. The firefighters are in front of a closed door. The door separates the compartment from the oven where a stack of pallets is burning. The fire has become ventilation controlled. Due to the overpressure inside, pyrolysis gases are pushed through the cracks that surround the door. *(Picture: Erik Etienne)*

It is now clear that the pressure in the room has an evolving character prior to backdraft. For firefighters, this is important. When opening the door to the room, the flows will be different depending on the pressure in the room. This explains why backdraft can be the result of different situations. When arriving at a door that looks like the door in Figure 7, it is clear that the risk of rapid fire progress is eminent. But a door that has no smoke showing can be very dangerous as well. There could be a fire in the negative pressure phase behind the door. Firefighters should keep this in mind when opening doors at the fire ground.

2.2.2.2 Pressure generated by the backdraft

The ignition of the flammable mixture is followed by the propagation of the flame through the mixture. This will cause an immediate pressure rise [1]. Weng et al [23] found peak pressures up to 87 Pa in experiments with a $1/4^{th}$ scale prop. The prop was fueled with methane. They find as well that the overpressure increases if the surface of the opening decreases. So the overpressure generated by a backdraft with a small window providing the fresh air will be greater than the overpressure generated in a room where the fresh air is flowing through a door.

Figure 8 Pictures from a video sequence at a fire in Harrison, New Jersey. It can be clearly seen how the overpressure generated by the backdraft pushes the window out of its opening. *(Pictures: screenshots from [24])*

Fleischmann et al [11] found values ranging from 4 to 73 Pa in their half-scale experiments. Gottuk et al [7] found values ranging from 85 to 234 Pa in their full-scale tests on board the USS Shadwell when the fireball entered a 191 m³ buffer zone. If the buffer zone volume was reduced to 104 m³ and then 20 m³, the overpressure rose to 1243 Pa. This shows that the overpressure increases when the volume of the buffer zone decreases.

Bolliger [1] did full-scale experiments in a shipping container. He used methane to fuel the experiments. The container measured 2.4 x 2.4 X 6m. The overpressure generated by the backdraft varied between 5.8 and 42.7 Pa.

Fleischmann performed experiments where the spark activation was delayed. In most of his experiments, the ignition spark was activated before making an opening. In some experiments, the spark was only activated after the gravity current reached the rear wall. He found that the pressure generated by the backdraft is approximately five times greater. This higher pressure can be explained. Due to the later activation time of the ignition source, more time is available for air to enter the container. Therefore the volume of gases that are in the flammable range will be bigger. It is likely that this last scenario where the ignition source becomes active after the making of the opening exists in reality. In such cases, the start of flaming combustion at the seat of the fire will act as an ignition source.

Gojkovic [6] recorded pressure measurements during his full-scale test series. He showed that the pressure in the compartment rises following the ignition due to the thermal expansion of the gases. The overpressure in the compartment is over 200 Pa. The gases flow through the opening to equalize the outside and inside pressure. This flow leads to an relative negative pressure in the compartment. A flow from the outside towards the compartment will try to equalize the pressure again. This will lead to an oscillating pressure with a decreasing amplitude until ambient pressure is reached (See Figure 9).

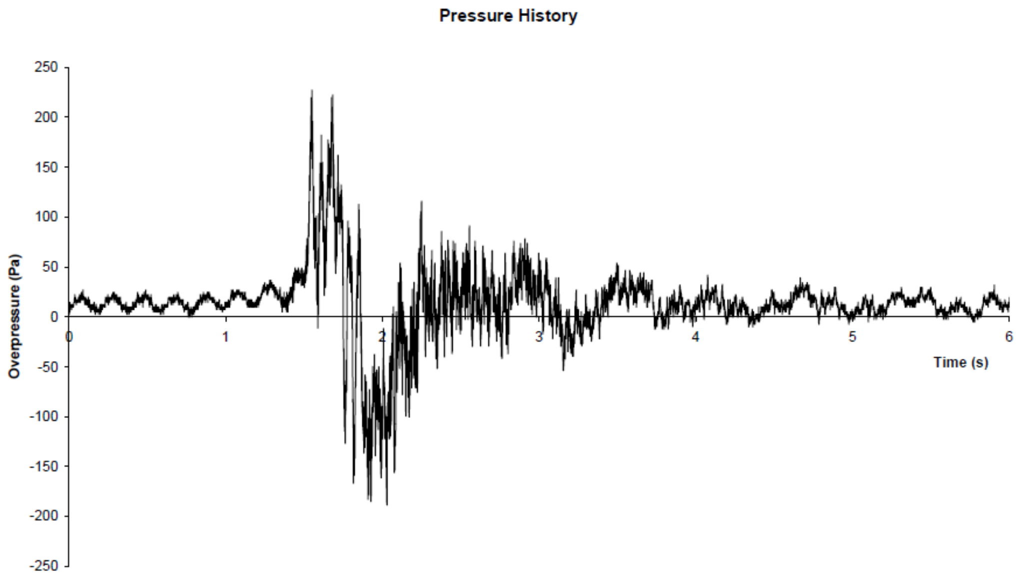

Figure 9 The pressure history during a full-scale test *(Graphic: Gojkovic [6])*

Objects in the room will act as obstructions. This will increase the severity of the explosion. The reflection should be made that the experiments cited above used rooms without objects. The pressures that have been recorded during those experiments may be an underestimation of the overpressures that can occur in reality.

2.3 Important factors

2.3.1 Ignition source

The ignition source is a very important parameter for backdraft to occur. In reality the ignition source can be supplied by flames, embers or hot surfaces in the room. Scientists use several ignition sources in their experiments.

Gottuk [7] mentions temperatures of the steel to be 390-450°C. This is a lot higher than the auto-ignition temperature of diesel (250 °C) that is used in the experiments. This implies that the hot surface acts as an ignition source in these experiments.

Horvat et al. [19] performed full scale tests in a shipping container. They used methane as fuel. They found that the ignition wire that was used during the experiments was not always capable of supplying the energy needed for ignition. Further they stated that the local flow conditions near the ignition wire have a significant effect. Several other researchers used heated wires as well. Weng [18] used an electrically heated wire with a power of 1200 Watt. Gojkovic [6] used an electrically heated wire as well but no details are given about the power of the device. He concludes that the ignition source is not reliable and needs a higher voltage to instantaneously ignite the gas mixture.

A spark is also frequently used as ignition source. Fleischmann [14] used a 10 000 Volt spark generator as ignition source. Bolliger [1] used a 15000 Volt spark as an ignition source. Furthermore, he concludes that if an ignition source is present throughout the experiments, ghosting flames will ignite and consume the excess fuel while there is still available oxygen. The consequence of this is that backdraft will not occur.

When evaluating these research papers, the link with reality should be made. In the experiments, very powerful sparks (ignition sources) are used. To which degree does this correspond with reality? It is not clear what acts as an ignition source in reality. Is the energy supplied by the glowing embers enough to induce a backdraft? Do there need to be flames to provide sufficient energy? Are the walls hot enough in an underventilated fire to provide the ignition source? In another hypothesis, based on firefighter experiences, it is suggested that hot gases might provide the energy for ignition. In that case auto-ignition of the fire gases would be the ignition source. This type of backdraft is called "hot backdraft". Further research into ignition sources for backdraft seems to be necessary to increase the understanding of backdraft.

A second reflection is that the fire will restart its evolution when fresh air comes available, regardless if backdraft is going to occur or not. In order for backdraft to occur, the fire needs a flammable mixture and an ignition source. In reality it might take a number of seconds before this is the case. So after the making of the opening, there is some time passing by before backdraft occurs. During that time the glowing embers might show flaming combustion. The energy provided by these flames is higher than the energy provided by the embers.

Mao [17] refers to this as gravity current delay and ignition source delay. In order to have a backdraft two conditions need to be fulfilled: the gravity current needs to create a volume of gases in the flammable range and an ignition source with sufficient energy must be created. When the latter is formed by the appearance of flames at the seat of the fire, it may take some time before the flames appear. Both processes take some time. The gravity current will need time to travel through the compartment until it meets an ignition source. And the ignition source (the flames or embers) needs time to create the energy needed for ignition of the flammable mixture. The delay between the making of the opening and the occurrence of backdraft will be determined by the process that takes the longest time to meet the criterion.

Gojkovic [6] reminds us that the time to ignition is also dependent on the mass fraction of combustible gases. If the amount of gases in the enclosure is very high, it will take more time to dilute the combustible gases to a mixture in the flammable range than if the mass of combustible gases is just above the critical mass fraction.

2.3.2 *Wind*

Wind is clearly an important factor. Bolliger [1] describes several experiments where the wind seemed to have an effect on the outcome of his experiments. One of the reasons that wind influences the outcome of a backdraft is that wind changes the pressure distribution over the surfaces of a building. In extreme cases wind is capable of sealing a window opening. In this way, the exit of fire gases is limited or even prevented. It is only when an opening is made on the low pressure side of the room, that the fire gases can exit the room. They will ignite when exiting. Extremely high temperatures can be reached in such circumstances. Fires where the wind has such an influence on the fire behavior are known as wind driven fires [21],[22].

While the influence of wind in a wind driven fire is well understood since the research projects of NIST, further research is necessary to fully understand the influence of wind on the occurrence of backdraft. It is clear that the direction and the velocity have a major impact but not all questions have been answered.

2.4 The outcome

After a backdraft, two scenarios are possible. Mao [17] states that a severe backdraft can result in a flashover. This will depend on the flow path of the backdraft. When gases are pushed towards the opening and pass through a room with a sufficient quantity of easily ignitable combustibles, the front of flames will set them on fire. Due to the extreme heat transfer, the objects will start to burn immediately. After the passage of the front of flames, all the objects will contribute to an increasing heat release rate in the room. The resulting fire will transition to flashover shortly after the backdraft. In such cases firefighters have to deal with a fully developed fire.

Figure 10 Image of a fire after a backdraft. No flames are visible in the compartment. Smoke exits and fresh air enters the volume. *(Picture: Benoît Amans)*

Another outcome which has been observed frequently at the fire ground is that the pressure wave generated by the backdraft knocks the flames down. The backdraft has the same effect on the fire as blowing out the flame of a candle. Because of the pressure wave, several openings are created in the envelope of the building. Windows tend to break and doors may be forced open. This leads to multiple openings through which fresh air can enter the building. In such cases firefighters are confronted with the same images as they meet when they make an opening to an underventilated fire. The compartment is completely filled with smoke. The upper part of the opening is used as an exhaust while fresh air enters the compartment through the lower part of the opening (See Figure 10). In this situation, firefighters have to deal with a fire which will start to grow because plenty of oxygen is available now.

2.4.1 Fire ball

The fire ball is a typical characteristic of backdraft (See Figure 11). It is nothing more than the ignition of the excess pyrolyzates outside of the building.

Figure 11 The excess pyrolyzates are pushed out through the opening. They will be ignited by the front of flames that is travelling towards the opening as well. This will result in the fireball that is typical for a backdraft. *(Picture: Ed Hartin [20])*

When the ignition has taken place, a small premixed flame front travels into the flammable mixed layer proceeding the large non-premixed deflagration [9]. The excess pyrolyzates are pushed in front of the pressure wave. Outside the opening a volume of combustible gases is created due to the outflowing smoke which mixes with air. This volume of combustible gases is ignited by the flame front that travels through the flammable mixture when it arrives at the opening.

Weng et al [23] found that the size of the fireball is proportional to the total hydrocarbons mass fraction. This has been confirmed by Mao et al [17] in their research about backdrafts in tunnels. When the total unburned fuel fraction increases, the resulting backdraft is more intense and generates a larger fireball.

2.5 Confusion: Smoke explosion

2.5.1 History

In early literature, no distinction is made between backdraft and smoke explosion. Croft [25] describes several explosions that occurred on the fire ground between 1906 and 1976. In his review he describes events that today would be called "backdraft", other events that would be called "smoke explosion" and other types of explosions. Especially early in the 20th century the two phenomena were confused. The two names were used simultaneously for the two phenomena.

In France this confusion is increased by the custom of translating English terminology into French. In 2003, the French ministry of interior edited the "Guide national de reference" concerning flashover and backdraft [26]. The term backdraft is translated as "explosion de fumées", which literally means "smoke explosion".

2.5.2 What is a smoke explosion?

Ed Hartin, a US chief fire officer and world-famous instructor, suggests the following definition for smoke explosion [27]:

"A smoke or fire gas explosion occurs when unburned pyrolysis products and flammable products of combustion accumulate and mix with air, forming a flammable mixture and introduction of a source of ignition results in a violent explosion of the pre-mixed fuel gases and air. This phenomenon generally occurs remote from the fire (as in an attached exposure) or after fire control."

As can be read in the above definition, a mixture of fire gases (smoke and pyrolysis gases) are introduced into, or produced in, a volume. There it mixes with air. This continues until the mixture reaches the lower flammability limit (LFL). The mixture remains ignitable until it reaches the upper flammability limit (UFL). The mixtures that are between the LFL and the UFL are indicated as, "in the explosive or flammable range". At one point the mixture of combustible gases and air is "ideal". This point is called the stoichiometric point. An ignition source is required to ignite a mixture in the explosive range. When the mixture is ignited, an explosion follows. The severity of this explosion is determined by the mixture itself and the confinement. The closer the mixture is to the stoichiometric point, the fiercer the explosion will be. The explosion will cause a pressure wave. The confinement will block this pressure wave. The higher the degree of confinement, the higher the overpressure will be.

In a fire, fire gases can leak to the adjacent room and create a flammable mixture. The energy source, needed for ignition can be provided by the fire that burns a hole in the separation between the two rooms. These flames can then ignite this mixture.

The smoke explosion belongs to the family of fire gas ignitions (FGI). A related phenomenon is a "flashfire". In this case the mixture is flammable but not ideally mixed. The ignition of this mixture results in flaming combustion without a pressure build-up.

2.5.3 Differences between smoke explosion and backdraft

Two important differences between backdraft and smoke explosion can be made. Firstly, there is a difference in the mixture of the gases prior to the phenomenon. In the case of backdraft, a fire has used most of the oxygen present in the room. The fire has produced large quantities of combustion and pyrolysis gases. This leads to a situation where the mixture is no longer ignitable due to a lack of oxygen. The mixture has passed the upper flammability limit (UFL). In the case of a smoke explosion, the mixture is in the flammable range and close to the stoichiometric point.

	Backdraft	**Smoke explosion**
Mixture	Above UFL	In flammable range
Induced by	Entry of air	Entry of ignition source

Table 1 Comparison of backdraft and smoke explosion

A second important difference is the element that induces the phenomenon. In the case of backdraft an opening is made. There is a density difference between the gases in the room and the outside air. This creates a gravity current. Smoke escapes while air enters. The mixture is diluted until it enters the flammable range. When flaming combustion reappears in the seat of the fire, the mixture is ignited and backdraft is the result. In the case of a smoke explosion an ignition source is introduced in the flammable mixture. The mixture ignites and a smoke explosion is the result.

3 Backdraft: Firefighting

3.1 Warning signs

The warning signs mentioned below must be evaluated as a whole. One should avoid attaching excessive importance to one sign. If, on the other hand, several warning signs appear, it is more likely to have a backdraft. It is not because the warning signs are present, that it is 100% sure that backdraft will occur. Actually, it is more likely to have a ventilation induced flashover than a backdraft.

3.1.1 Puffing smoke

The warning sign that made backdraft infamous, is the presence of puffing smoke. In the movie "Backdraft", the smoke was seen coming through the gap under a door. Next it was sucked back into the room through the same gap. This image is a little exaggerated. The behavior that can be seen on the fire ground is that of smoke being pushed through the gaps that surround the door (See Figure 7 and Figure 13).

When the fire becomes extremely ventilation controlled, the combustion inside will stop. The temperature inside will stabilize and eventually it will start decreasing. The overpressure inside will disappear. The flow of smoke through the gaps will stop. After a certain time, a reverse flow can appear. Fresh air is now drawn into the compartment. This can turn into a cycle where flows that are exiting the room are alternating with flows going in.

Though a lot of attention is given to the gaps around the door, smoke can also exit from gaps around windows. Sometimes smoke can be seen exiting from beneath the eaves of the roof. A light flow of smoke leaving the building through the gaps between the roof tiles has been reported as well.

3.1.2 Darkened windows

A second sign of impending backdraft are "blackened windows". The hot fire gases are driven away from the seat of the fire. They are mixed with air and the temperature of the resultant mixture is lower. When these fire gases hit a window, their temperature will drop even more. The cold window causes condensation of the fire gases. This process is similar to what can be seen in a kitchen during cooking. The water vapor that is produced also condenses upon contact with the cold windows.

This process results in oily deposits on the windows. These deposits are not always black. Colors such as grey and dark and light brown are reported as well (See Figure 12).

Figure 12 A firefighter starts horizontal ventilation. The oily deposits are clearly visible on the windows. These deposits have a brownish color. *(Picture: Bill Murton)*

3.1.3 No flames visible

When looking at the mechanism behind backdraft, one knows that the mixture in the room has to be above the upper flammability limit prior to backdraft. This means that no combustion is possible in that compartment. However, it should be considered that the mixture in a room is never homogenous. Therefore, it is possible that pockets of gases may burn locally in the room. Chitty [3] mentions the appearance of blue flames. Grimwood [36] mentions pockets of gases that ignite in an environment that is clearly ventilation controlled. The same phenomenon, local combustion in the smoke layer in an underventilated room, has been observed repeatedly by the author during CFBT training exercises. In those cases flames had a range of colors going from yellow to greenish-blue.

It is important to interpret this warning sign correctly. The absence of flames indicates the possibility of a backdraft and the presence of an underventilated fire. One cannot reverse this rule. The presence of flames does not mean that the chance of backdraft is impossible.

When arriving at the scene of a fire, firefighters may see a blackened window while flames are clearly visible through another window. The fire can even be venting through that second window. This should not lead us to believe that backdraft cannot occur. The two windows can belong to different and separated rooms. A ventilated fire can be burning in the second room while an underventilated fire is hiding behind the first.

A second possibility is the presence of exterior flames that seem to come from the compartment as discussed in the Covée case (See 3.3.1). In that case, flames were also present but this didn't exclude the occurrence of backdraft.

3.1.4 Radiant heat

In the case of a pre-backdraft situation we can have a fire that has filled the compartment with hot fire gases. These gases will transport heat through the boundaries of the compartment. This means that construction elements with a high conductivity will heat the other side as well. In the case of windows the temperature at the outside can be so high that the radiant heat can be felt by a firefighter passing by.

Especially large windows can start to act as radiators. In such a case firefighters can notice a dark colored window that radiates heat. It is important that they communicate this finding to incident command. To a certain degree the description above is applicable to metal doors as well.

3.1.5 Sounds

In firefighting literature whistling sounds are described as a warning sign for backdraft. When a door is opened to a compartment with a pressure difference with the outside, a current will be created to neutralize the pressure difference. This flow can cause a whistling sound.

This is a very late warning signal. Actually it is too late to prevent backdraft at such a moment. Whistling sounds can only warn people on the fire ground. It tells them that something might happen in the moments that follow.

3.1.6 Sudden inrush of air

Another very late warning sign of backdraft is the inrush of air when an opening is made. It is not because air rushes in that there will be a backdraft but an inrush of air indicates that something might happen.

Figure 13 The smoke that is pushed through the gap is so hot that it auto-ignites at the outside of the compartment. This indicates an overpressure inside the room and the presence of a fire that is or has been very intense.

In a case of backdraft in France, firefighters narrated afterwards that they couldn't hold the door when they opened it. Due to the inrush of air, the door was drawn in a completely open position. The air current was so strong that the firefighter who opened the door couldn't hold on to it. A little time later, backdraft occurred. Both firefighters were smashed against the opposing wall in the hallway. Luckily, both were wearing full PPE and they survived the incident.

The pressure evolution in the room prior to backdraft is discussed in paragraph 2.2.2.1. This results in a certain overpressure or negative pressure acting on the door. In general, a door opens inwards or outwards. In Belgium, firefighters encounter mostly inward opening doors on their way to the seat of the fire. In such a case, it may be difficult to open the door if there is an overpressure. This will be clearly visible by smoke that is being pushed through gaps. If there is a negative pressure acting on the door, the scenario discussed above can become reality. Probably, no smoke will be showing. Before the negative pressure phase, there has been an overpressure in the compartment.

Smoke has left the compartment through any gaps. It may happen that there are indications that smoke has left the compartment.

Figure 14 Picture of the garage door taken after the fire. The door has now been forced and was partially in the open position during firefighting. The image that could be seen prior to the first opening has been changed due to water and steam from the extinguishment. Prior to the first opening only the two upper parts were colored due to deposits. The four lower parts were completely clean.

The author experienced such a case where no smoke was showing in 2007. The fire service had been called because somebody noticed smoke outside a large industrial complex which housed several companies. The call was received in the middle of the night. When crews arrived on scene, nothing was indicating there was a fire. During the reconnaissance, two ladder trucks were deployed at full length (30m) in order to have an overview of the premises. Thermal imaging cameras were used but nothing was found. Nobody could detect flames, smoke nor heat. In this case, the smoke had put oily deposits on the garage door, which was 4m high and 3m wide. The oily deposits made it possible to identify the compartment in which there was a fire. It was only after half an hour of searching in the dark, that the oily deposits on the door were discovered. When the door was opened, there was a massive inrush of air. Luckily, there was no backdraft because this would probably have resulted in multiple casualties amongst firefighters. At that time, the risks of underventilated fires were poorly understood and the author acted accordingly. The heat release rate of the fire peaked immediately after the opening of the door and the fire went through the roof. The fire service had great difficulties in extinguishing the fire. The compartment turned out to be a garage/workshop with 22 cars and 2 trucks inside. The compartment measured 48 by 14 meter. Part of the roof covering collapsed during the firefighting process. With modern tactics, the risks of fighting this fire could be decreased.

3.1.7 No warning signs at all

In his blog, Ed Hartin published a number of posts discussing the research projects performed by UL regarding horizontal and vertical ventilation [37]. Hartin mentions the absence of visible indicators of fire behavior by using the quote “Nothing showing means exactly that. Nothing!”.

The negative pressure may be the cause of the absence of warning signals. For firefighters it is impossible to know at what moment in the pressure development they arrive on scene. Several fires [38] have been reported where there is heavy smoke showing prior to the arrival of firefighters but no smoke is showing at the moment firefighters arrived on scene. The author experienced a fire where lightning had struck a single family dwelling and caused massive pyrolysis in one wooden beam of the roof. This caused the showing of lots of brown-colored pyrolysis gases immediately after the lightning strike. A volunteer chief officer was nearby and witnessed this. By the time the fire engine arrived on scene, nothing was showing but the fire was approached with extreme caution. When the roof was opened, it showed that the wooden beam had self-extinguished. So, even with nothing showing after the release of large quantities of smoke doesn’t mean that there will always be an event of rapid fire progress.

Hartin concludes that fires where there is nothing showing should be treated as underventilated until proven otherwise. This is a very wise position. All fires should be approached with caution. Typically, underventilated fires are fires which are temporarily “stable”. There is time needed to do a proper 360° size-up and to make the necessary preparations before making an opening.

Lastly firefighters should be aware of the fact that warning signs may be difficult to notice at night. Windows that have oily deposits or that are discolored might not be noticed by the firefighters on scene. The same goes for small quantities of smoke that are exiting from the building. In the darkness, it is possible that those cues are not noticed because it is difficult to see them.

3.2 Possible tactics

It has been described above that backdraft is a fierce phenomenon that represents a real danger to the firefighters that are confronted with it. Several factors should be taken into account by the incident commander (IC) when he/she decides on the actions to be taken. In a dynamic risk assessment (DRA), the IC should evaluate the risks and the gains continuously during the fire service intervention.

It is clear that the atmosphere in a pre-backdraft situation is not survivable for civilians in that compartment. On the other hand, it has been shown that a survivable atmosphere can exist in the adjacent rooms if the door between the rooms is closed. The atmosphere in the second room will get more and more polluted so the survival time of the civilians inside is limited.

Depending on the resources, the size of the building and the presence of civilians, the IC can select one of the options described below. The best option is to introduce water into the gaseous mixture. This is called “gascooling” by firefighters but scientists have shown that the cooling effect is secondary and the diluting effect is more important. The fire gases inside can be cooled and diluted by applying several tools.

Another tactic is ventilation. When this tactic is applied, the goal is to try to remove the fire gases before they can ignite. This can be achieved with natural ventilation or by using fans. Ventilation implies adding fresh air. This can lead to backdraft so ventilation can be dangerous.

A last tactic is to choose to induce the backdraft. In these scenarios the IC considers the backdraft inevitable. He or she chooses to have the backdraft at a moment that all personnel on the fire ground are prepared. This is still a better option than having a backdraft during the intervention when it is unexpected.

3.2.1 *Cooling/diluting the gases: theory*

Gascooling is very well known as a technique to deal with fire gases in major parts of the world by the firefighting community [36]. In science more attention goes to the diluting effect that the water vapor has on the mixture. In this paragraph, both approaches to the introduction of water in an environment with fire gases are discussed.

3.2.1.1 A firefighting approach

Hot fire gases contain large quantities of energy. By introducing water into the gases, the temperature will drop. The cooled mixture will need a higher ignition energy. By cooling the gases, the probability of an ignition is lower.

Cooling the gases also has a second effect. When the cooled mixture is ignited, the resulting explosion will be less severe. The cooled mixture contains a lot of steam and it functions as a thermal ballast. The speed of the fire reaction shows an exponential relationship with the temperature. This is called the Arrhenius expression. A cooler mixture will thus result in a phenomenon that is several times less severe.

Lastly, the produced steam will dilute the mixture. Steam is an incombustible gas. Therefore the mixture will be rendered inert. If the water is introduced without creating a large opening, an overpressure will be created in the room. A mixture of steam, combustion gases and pyrolysis gases will be pushed through cracks and openings. When the overpressure has disappeared, there will be less fuel left in the compartment.

Two factors will play a dominant role to determine whether the water application will be successful: the diameter of the water droplets and the reach of the water stream. In order to transform a high proportion of the water into steam, the droplets must be sufficiently small. Otherwise the droplets will fall through the smoke and land on the ground without turning into steam. A water stream will leave the room under the door and the cooling effect will not be optimal. The droplets have to be sufficiently big as well to have a certain reach. To have an optimal cooling effect, the droplets produced by a handheld nozzle should be in the order of magnitude of 0.3 millimeter [36].

Besides a good droplet size, it is important as well that the water droplets are capable of cooling the complete volume in the enclosure. Therefore the reach of the water stream has to be far enough. In a large volume, it will not always be possible to cool and dilute all the fire gases.

3.2.1.2 A scientific approach

Gottuk et al. [7] found that water injection can be used as a mitigating tactic to suppress a diesel fuel backdraft. Injection of water results in a decrease of the fuel mass fraction because the water turns into steam. The resulting overpressure pushes the gases in the room through holes and cracks (See Figure 17). The gaseous fuel will exit along with the exiting steam. Gottuk and his team conclude that the mitigating effect is dominated by the decrease in fuel mass fraction and the dilution of the atmosphere. The cooling is less important. The prevention of backdraft is realized by decreasing the fuel mass fraction below the critical value of 16% in the case of a diesel fire.

Guigay et al. [39] remarked that the cooling of the gases will reduce the density difference between the smoke and the fresh air. This will reduce the speed of the gravity current. If it takes more time to create a flammable mixture, firefighting crews have a longer time frame to extinguish the fire. This is a second reason why introducing water improves the conditions.

By doing a CFD analysis, Guigay et al found that dilution is very effective if the critical fuel volume fraction (CFVF) is reached. When water is brought into a fire environment and the CFVF is not reached, the cooling will lead to a situation where the densities of the gases are equalized before the combustible mixture has left the room. Due to the cooler gases, the temperature (density) difference between the smoke and the air will be smaller. In such cases the efficiency of natural ventilation drops and natural ventilation is no longer an option.

In science flammability diagrams are used to study mixtures [39]. Such a flammability diagram can be found in Figure 15. The diagram on the left side represents a gas mixture prior to the use of water. The base of the triangle shows the volume fraction of oxygen in the mixture. The left side of the triangle shows the volume fraction of methane while the right side of the triangle shows the volume fraction of nitrogen. Using such a diagram to study backdraft implies a number of assumptions. First of all, it is assumed that methane represents the unburned fuel as in several research projects discussed above. Secondly, the diagram disregards that in a real fire, there will be combustion products as CO_2, CO, HCN, … Neglecting these gases is acceptable because their contribution to the mass balance is limited. Furthermore, it is assumed that the mixture is well-mixed. In pre-backdraft mixtures, this is an acceptable assumption. Lastly water vapor is considered an inert gas and is "added" on the right side of the triangle.

A couple of examples will make things clearer. In clean air, there is 21 volume percent of oxygen and 79 volume percent of nitrogen. This ratio can be located on the base of the triangle in the point A. In Figure 15, a mixture of 43.6 Vol.% methane, 44.7 Vol.% of nitrogen and 11.7 Vol.% of oxygen is indicated with the blue lines. It is noted as D(30) because a volume fraction of 43.6% of methane equals a mass fraction of 30%. It can be noticed as well that the sum of the three volume fractions is 100%. This should always be the case.

If one wants to dilute a certain mixture with air, a line can be drawn from that point to A. During the dilution process, the gas mixture will follow the compositions determined by the line. A mixture with 100% methane can be located in point C in the top of the triangle. The dilution of such a mixture with air follows the line C-A, which is called the "air line".

Every flammable gas has a range of mixtures where the ratio with air and inert gases allows it to burn. All the possible flammable mixtures are indicated in the red zone in Figure 15. When looking at the line C-A, it is noticed that it passes through this zone. It enters this zone at 15% methane and leaves this zone at 5% methane. These values are known as the UFL and LFL of methane. This means that the mixture which wasn't flammable before becomes flammable while diluting it with air. This is a risk that should be avoided if possible.

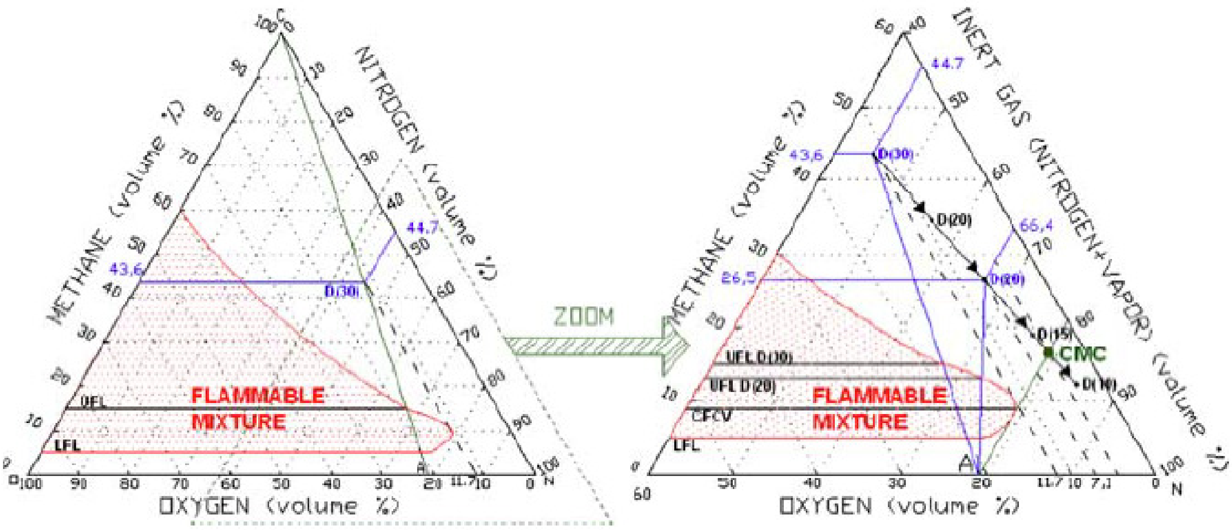

Figure 15 A flammability diagram and the influence of diluting water in the mixture [39].

The right diagram in Figure 15 shows the effect of introducing water in a hot gaseous mixture. The water turns into vapor and the ratio between the gases changes. Water vapor is considered inert and can be added with the quantity of nitrogen. This causes a change in the initial mixture.

The point D30, which represents a fuel mass fraction of 30%, can be located in the right diagram. A line connects this point with the point A, which represents air. It is clearly visible that diluting a mixture D30 with air creates a flammable mixture at a certain point in time. The line goes through the red flammable zone. When water is applied in the volume, the steam changes the mass balance. When the mixture is diluted with water vapor so the fuel mass fraction is only 20%, the point D20 is reached. When this mixture is further diluted with air, the line still goes through the flammable range but during a smaller number of possible concentrations. When enough water is applied to dilute the mixture to D15, it can be seen that the line that connects D15 with A doesn't go through the flammable range. This means that the application of water (vapor) has rendered the mixture harmless. This is the principle that needs to be applied in a pre-backdraft situation.

The idea is to apply two steps:

1. Apply water in the mixture so that the vapor dilutes it until the mixture becomes harmless.
2. Open up and remove the smoke, which causes to dilute the mixture even further with air.

3.2.2 Cooling/diluting the gases: practice

Several options are available to introduce water in the room. The most popular ones are explained in detail below.

3.2.2.1 Gascooling with a handheld nozzle

Firefighters have lots of experience with gascooling. When advancing towards the seat of the fires, they are supposed to cool the gases in the overhead in order to prevent flashover. But when firefighters are confronted with a pre-backdraft situation, gascooling is usually not the first thing they think about.

It is possible though to apply some kind of gascooling. Other than the normal gascooling techniques which require short or long pulses with a low flow, firefighters should select larger flows (e.g. 500 LPM). One firefighter should open the door to the compartment. Another firefighter should apply water with a 30° fog setting. While operating the nozzle, the firefighter should make a couple of circles in the door opening to ensure that all the hot surfaces in the compartment are hit by the water droplets. When this is accomplished the door should be closed again. A short piece of rope can be attached to the door knob to be able to close it again if the door opens inwards. The introduced water will convert into steam. This will not only cool the gases in the compartment but it will dilute the gases inside as well. If necessary, this procedure can be repeated multiple times until there is no more positive or negative pressure in the room. The general idea is to absorb heat and produce large quantities of steam to render the mixture inflammable.

3.2.2.2 Gascooling with piercing nozzles

The technique described above is used when no special equipment is available. The disadvantage of the technique is that air rushes in when the door is opened. This might lead to a rapid backdraft before the firefighters can achieve sufficient dilution/cooling. In an ideal situation, it would be more beneficial to inject water into the compartment without air entering the compartment.

Figure 16 A piercing nozzle that disperses its water droplets radially *(Picture: John Norman)*

Such a solution would be applicable as well for underventilated fires which will not lead to backdraft. The piercing nozzle is a tool that enables one to disperse water on the inside of a compartment without admitting air. Often it is used in combination with a drill. A hole is drilled through the compartment wall or door. The piercing nozzle is placed into the hole and the water valve is opened. There exist several types of piercing nozzles. Their length shows great variation and models exist which are long enough to go through a wall that is heavily insulated.

The piercing nozzle is designed to disperse droplets of water in the burning room. The stream of droplets can have a radial pattern (See Figure 16) but there are also types which create a forward cone of droplets. Firefighters have to know the equipment they have available and select the most appropriate nozzle for the job.

Figure 17 Application of the piercing nozzle to prevent backdraft in a training setting at the MSB Revinge fire academy *(Pictures: Lars Ågerstrand)*

When a compartment contains hot gaseous fuels, the conditions to create backdraft might be met. By introducing water droplets into the hot mixture, large quantities of vapor are formed. Because of this, an overpressure is created in the compartment or the existing overpressure is increased. The resultant overpressure will cause a massive outflow of gases (fuel and vapor) through openings and gaps. This result can be observed in Figure 17. This flow will continue as long as water is dispersed into the compartment. In a very short time, the fuel mass fraction inside will be decreased below the critical value and backdraft becomes very unlikely.

3.2.2.3 The cobra cutting extinguisher

A more expensive tool that enables firefighters to inject water into a compartment is the Cobra cutting extinguisher (See Figure 18). This tool combines the capabilities of the piercing nozzle and the drill. Moreover, due to the ultra-high pressure, the droplets are finer and their reach is larger than those produced by a piercing nozzle.

The cobra is a special kind of tool that is equipped with a pump that can deliver a pressure up to 300 bars. The flow rate is typically 30 or 60 LPM. The operator starts the cobra by applying a jet of water on the building element he wants to penetrate. In order to do so, an abrasive element is added to the water after the pump. Therefore a by-pass is going through a vessel filled with small abrasive balls. The combination of the ultra-high pressure and the abrasive elements enables the cobra to cut a hole in many varied construction elements (window, door, wall, floor, beam, …). When the hole is made, the supply of abrasive is stopped. Then the water jet of the cobra continues to flow into the compartment. The gases in this compartment are diluted and the temperature drops.

Figure 18 The Cobra nozzle. When both the triggers are pulled, both water and abrasive flow through the line. When only the blue trigger is pulled, only water flows. The orange block is the radio transmitter that sends signals to the pump. *(Picture: Cold Cut Systems Svenska AB)*

Guigay et al. [39] write that tools like cutting extinguishers and piercing nozzles have a low flow rate but that this should be sufficient to dilute the volume of smoke in a standard apartment. Firefighters should take this into account when they are confronted with a backdraft risk in a larger structure. The use of multiple piercing nozzles or multiple cobras can be a solution in some of these cases.

3.2.2.4 The cobra system

A complete tactic has been designed for using the cobra technology [40]. The idea behind it is that the cobra is capable of knocking down the fire but can't extinguish it. So after application of water, firefighters need to enter the compartment to perform the final extinguishment.

The tactic consists of 4 phases:

1. Size-up
2. Application of cobra: cooling and diluting
3. PPV
4. Interior attack

As indicated above, an underventilated fire which shows no openings to the outside behaves as if somebody pushed the pause button. There is time to do a complete size-up. The officer on scene can use the thermal imaging camera (TIC) to see where there are hot spots. It is highly likely that the fire is somewhere near these hot spots. By performing the size up, the officer determines where the cobra has to be put into action.

Figure 19 Application of the cobra at a fully developed fire during a training course with the cobra cutting extinguisher. *(Picture: Willem Nater [40])*

In the second phase, one or multiple cobras are used to cool down the gases in the structure. Ideally windows and doors are used to position the cobra. The water jet penetrates fast through such construction elements. A second advantage is that the water jet will go into the compartment because it is very likely that no object is behind the window or the door. When the cobra is used to penetrate a wall, the water jet might end up in a closet next to the wall. If there are rooms where pre-backdraft conditions exist, the produced water vapor will dilute the gases. The critical fuel mass fraction will no longer be attained and the risk of backdraft will disappear. While crews are working with the cobra(s), the officer checks with the TIC to determine how the situation is evolving. When he is convinced that the cooling phase is finished, he orders to open up the compartment. In a fire in Lund (Sweden) cobra was applied for 45 minutes before the officer decided to start to ventilate the structure (See Figure 20). Damage afterwards was limited to the immediate surroundings of the seat of the fire.

After application of the cobra, the structure (or at least multiple rooms) are full of a mixture of water vapor and smoke. Though the temperature will be limited, it is still not a very pleasant environment for firefighters. The visibility in the structure will be very limited. To get rid of the smoke, positive pressure ventilation (PPV, see below) is applied. One or multiple exhaust openings are selected. One or more PPV fans are put into place.

Figure 20 Fire in a school in Lund in 2009. The roof space is burning but due to a lack of oxygen, the fire is underventilated. It is feared to have fire spread or rapid fire progress when the roof is opened. Therefore cobra is applied during 45 minutes prior to opening the roof. The damage to the building was limited to the roof space. *(Picture: Patrick Persson – © Cold cut systems)*

When the openings are made, the fans are started. The cooled smoke is pushed from the structure. This leads to an improved visibility and to better conditions for the firefighters.

The last phase, interior attack, is started immediately after the start of the fans. Since the cobra has knocked down but not extinguished the fire and since the ventilation is removing the smoke and is adding fresh air, flames will start showing at the seat of the fire. The goal is that the fire attack crew advances a hose into the structure, finds the seat of the fire and extinguishes it. Due to the application of the cobra, the smoke has been cooled and diluted. This decreases the risk for the interior attack crew significantly. Due to the improved visibility, the seat of the fire should be found quickly. In these conditions, it is easy for the fire attack crew to achieve their objectives.

This tactic implies that the crews work as a team. The four steps need to be executed correctly and timing is crucial.

3.2.2.5 The use of straight stream

The use of straight stream at the scene of an underventilated fire generates a risk when the jet is aimed from the outside towards the inside. The straight stream will put a venturi system in place. The fast moving water jet will entrain a large quantity of air. Due to the water jet, this quantity of air will be "injected" into the underventilated fire. Such an injection of air can cause a backdraft.

3.2.3 Ventilation

3.2.3.1 Natural ventilation

Natural ventilation consists of making openings. Typically at least two openings have to be made: an inlet opening and an exhaust opening. If possible, the size of the inlet opening needs to be double of the exhaust opening [41]. In traditional fire services courses, this approach is the only approach that is mentioned.

Tuomisaari [10] writes that vertical natural ventilation is the safest method when faced with the risk of backdraft during a fire. This is because the concentrated heat and smoke will be released first when vertical ventilation is applied. Furthermore, vertical ventilation is more efficient than horizontal ventilation.

Fleischmann [14] warns that ventilation may induce backdraft. It is very important to take this into account. When ventilation is applied as a tactic in a situation where firefighters face backdraft, this should be done only when all fire service personnel are outside the burning building. This rule should be respected regardless of whether the ventilation is natural or forced.

3.2.3.2 PPV

Positive Pressure ventilation (PPV) or forced ventilation is a tactic which can be more efficient than natural ventilation.

PPV implies the usage of a positive pressure fan (See Figure 21). The fan creates a cone of air that blows into a room or a building through an inlet opening. This flow causes the pressure in the room or the building to rise above the ambient pressure. Because of the pressure difference over the exhaust opening, a second flow is generated. This flow is started from the room towards the outside. The final result is a flow from the fan through the building. This flow is capable of taking smoke particles along with it. In this manner, the building can be rendered smoke free.

A main difference is the ideal size of the openings. When applying PPV, the exhaust opening should be twice as large as the inlet opening. This is the inverse of the ratio that should be applied during natural ventilation [41].

If PPV fans are used in a correct manner, it is possible to remove the combustible gases from the building. On the other hand, the fan will generate a lot of turbulence. This will enhance mixing along the air track. A flammable mixture will be created. If this mixture meets an ignition source, a backdraft may be produced. Guigay et al [39] found that the higher the flow rate of the fan, the faster the smoke will be removed. By doing so, the existence of the danger is limited in time. Using PPV as a tactic can be successful but the firefighters have to keep in mind that backdraft can occur because an increase in flow rate generates an increase in turbulent mixing. Guigay et al concluded that the correct application of PPV increases the risk of backdraft significantly during the first seconds but this risk decreases quickly.

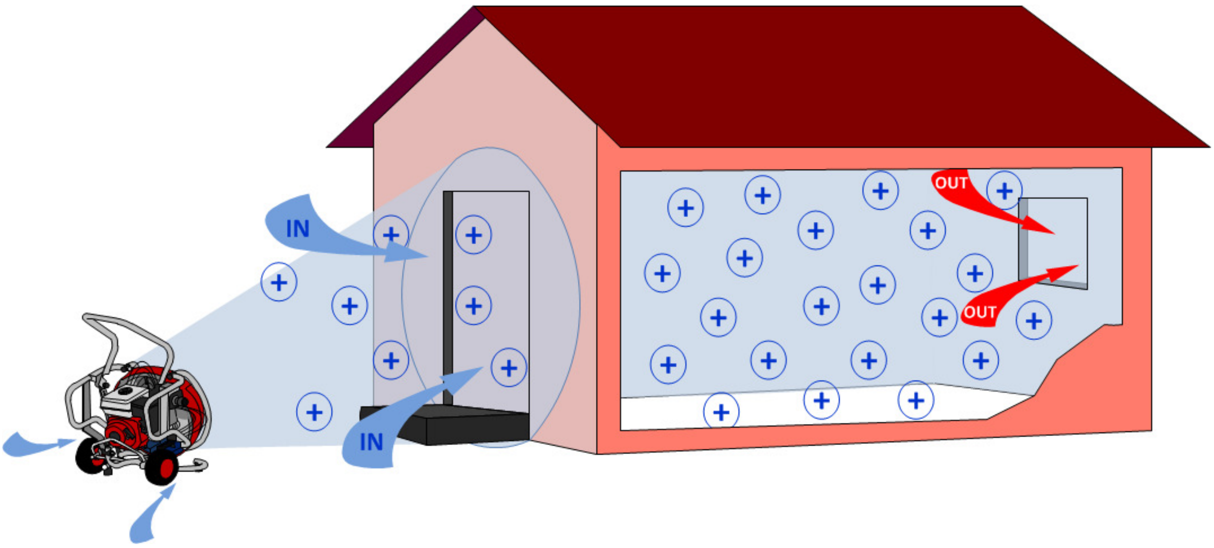

Figure 21 The principle of positive pressure ventilation *(Picture: Bart Noyens)*.

In their study, Guigay et al. also looked into the incorrect application of PPV. They considered the possibility that a door may close between the inlet opening and the outlet opening. If this situation occurs the efficiency of the ventilation drops drastically. The fan will cause turbulent mixing of the gases present in the room. This will create a flammable mixture that will remain in the room for a long time. They conclude that incorrect application of PPV will increase the risk of backdraft. PPV should not be applied when the geometry of the rooms is not known.

In Salt Lake City, a tactic called positive pressure attack (PPA) was developed. Kriss Garcia [42] writes that it is possible to use positive pressure fans prior to the fire attack. After the air current is started, the fire attack crew enters the building. In this way they can search the fire in a smoke free environment. This tactic could be a possible way to deal with a pre-backdraft situation as well but more research about the interaction between the airflow and the fire is necessary. Garcia mentions as well that some firefighters have to be appointed to ventilation tasks. Guigay et al. [39] mentions that the use of PPV implies that more personnel is needed on the fire ground. Therefore a standard operation procedure should be implemented in fire departments that want to use PPV or PPA.

Tuomisaari [10] writes in his report that it is claimed that an unrecognised backdraft situation will explode once a window or door is opened, long before the PPV fans have been turned on. On YouTube, several movies can be found where a door to a training prop is opened and it is only when PPV is started, that backdraft occurs. This leads to the conclusion that the claim above is not (always) correct.

3.2.3.3 Anti-ventilation

An underventilated fire in a closed building can be considered as a fire that has been "paused". As long as the building remains closed, very little change will occur. In modern buildings this can be expected for a certain amount of time. The fire service can use this window of opportunity to start their operations.

When the fire service arrives at the fire ground, some time is needed to make all the preparations. Often this is combined with or done after the reconnaissance. When the different tasks are performed in that order, an opening to the building has been made, air is flowing in and the clock is ticking. When anti-ventilation is applied, the reconnaissance happens only at the outside (a 360° size up). It is only when all the preparations are finished that the compartment will be opened. This leads to a better coordinated and safer fire service intervention.

3.2.4 Induce the backdraft

The last option to deal with a pre-backdraft situation is to induce the backdraft. This approach can be used in a situation where there are no resources to prevent backdraft from occurring or where backdraft seems unavoidable. When choosing this option, one hopes to have backdraft at a moment one chooses and not later during the intervention as a surprise.

The idea behind the tactic is that once backdraft has occurred, the risk for the firefighters is reduced. It is important though, that all people on scene are aware of the chosen approach. Everybody should have a safe position and several hose crews should be prepared to attack the fire after the backdraft.

Backdraft can be induced with a PPV fan. The fan can be started without an exhaust opening being made. The fan will generate a significant amount of turbulence and this will introduce large quantities of fresh air. It is very likely that the incoming flow will improve the mixture of the gases and it will probably restart the original fire. By doing so, the gaseous mixture becomes flammable and an ignition source is created.

It is possible to use natural ventilation as well. This is the same application as described in 3.2.3.1 but now the goal is not to prevent backdraft but to induce it. In buildings were vertical natural ventilation is not possible it may happen that backdraft is unavoidable. In such cases, it is better to begin with controlled natural ventilation and wait for backdraft to occur. At least, no firefighters will be injured or killed in the process.

Another method to induce flashover utilises the Venturi principle. When a water jet is aimed into a building, large quantities of fresh air are drawn by the water jet into the building. In this way, it is possible to "inject" air into an underventilated fire. Cases where such an approach induced the backdraft can be found on YouTube. In the window cell (See Figure 6) it is possible to induce the backdraft by giving pulses with a spray in the lower region of the door. Often a cone with an interior angle of 30-60° is used to give the pulses.

3.3 Cases

Several cases of backdraft are well documented in literature [25]. In Belgium, a fire in a food store lead to a violent backdraft. In the framework of a training program organized by the Belgian government, the author was able to interview several of the firefighters who were on site that day. A brief description of that event and the testimonies of the firefighters on scene will be given below. One of the most well-known cases is the backdraft at Watts Street in New York. This case will be discussed as well. A Belgian case of smoke explosion that took the lives of two firefighters in the fire department of the author will also be discussed.

3.3.1 Backdraft in Belgium: fire at Covée

A known case in Belgium is the fire that took place at a store called Covée [5], [28]. Covée is a retail chain that sells mainly frozen food. In the shop there are lots of freezers which can be opened by customers to select frozen products. The shop is part of a shopping mall with several shops. Both the exposures (left and right) are shops. On the left side, there is an Aldi, a retail chain of shops where one can buy groceries at a cheap price. On the right side, there is a shop called JBC. This is a retail chain of shops where one can buy clothing. The fire department receives a call on Sunday for a fire in the shop. In Belgium, most shops are closed on Sunday. This means that the fire service is confronted with a closed building. Due to the size of the building containing five shops, it is time consuming to do a full size up. During size-up, firefighters normally perform reconnaissance of the situation.

Figure 22 The view at the shop on arrival of the first engine. External flaming is clearly visible above the roof. *(Picture: Benoît Amans)*

Figure 23 Backdraft after making an opening in the glass wall. *(Picture: Benoît Amans)*

The parking lot in front of the shop is empty. A policeman is already on site and informs the crew of the first engine that the fire has gone through the roof (See Figure 22). The fire seems limited to the food store. Firefighters find difficulty in gaining entry to the building. The decision is made to use forcible entry to access the shop. An opening will be made in the glass wall in order to do an interior size up and start extinguishment.

More units arrive on scene. Extra units are a water tender and a ladder truck. Preparations are made to start the operations. Forcible entry tools are taken from the engine, hoses are placed and the ladder truck receives the order to start a master stream operation. The firefighter who is ordered to make an opening in the glass wall, decides to do this at the last window from the left (See Figure 22). His reasoning is that the brick wall can protect him from fallen glass. In a conversation with the author, he told that he tried to make a hole in the upper side of the glass wall with a sledge hammer but he wasn't able to because the glass was too resistant. In a second attempt he uses the weight of the sledge hammer to create a hole in the bottom side of the window. Because of the self-weight of the sledge hammer, he is successful in creating a hole with a 15cm diameter. He explains that air starts rushing in through the hole. The hole glass wall seems to bend inwards.

Shortly after there is a very fierce backdraft (See Figure 23). Luckily, all personnel on site was able to hide behind walls or was shielded by the fire engines. Nobody was hurt during the backdraft. The backdraft was so violent that the fire in the shop was nearly extinguished by the explosion. Firefighters entered the shop with 45 mm hoselines and were able to take control of the situation. Afterwards some firefighters on scene were astonished that such a phenomenon could have happened. They had been told that a backdraft could not happen when there were flames visible.

Some in the fire community think that the flames that can be seen in Figure 22 are the result of a phenomenon called auto-ignition. The hot gases from the shop are exiting through the roof. In the shop there is a mixture of hot gases that is too rich to burn (above the UFL). In the outside air, these hot gases mix with fresh air. The resulting mix enters the flammable range. Due to the temperature of the gases, this newly formed mixture ignites. If this were the case, then the ignition source of the backdraft could be the temperature of the gases in the shop.

3.3.2 Watts street

The fire department of New York (FDNY) has literally thousands of fires each year. March 28th 1994, there was a call for a chimney fire in 62 Watts Street. Three engines, two (ladder) trucks and a battalion chief are dispatched to the fire. Upon arrival they see that the building is constructed of masonry and was built during the 19th century. It is 14 m deep and 6 m wide. The total surface per level is 84 m². There are four floors, one below grade and three above grade, with an apartment on each floor. Such buildings can be found in every major city in the US and throughout Europe. Often, one or multiple floors have been renovated. Single glazed windows have been replaced by modern windows to reduce energy losses. Nowadays, measures are taken to reduce air currents. Buildings used to have lots of gaps and cracks through which heated air escapes. In new construction special films are used to prevent this from happening. In renovations, one tries to achieve an air-tight situation. Due to renovations, a building can behave differently than one might expect when looking at the front façade. In this particular building, the windows had been replaced. Heavy thermal insulation and sealing was installed. The building was described as being very tight [29].

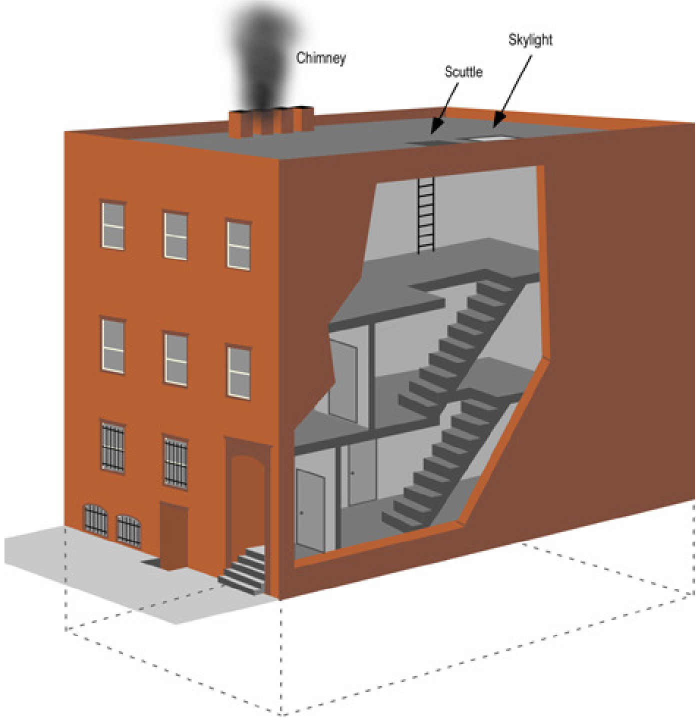

Figure 24 View on the staircaise of the building *(Picture: Ed Hartin & Richard Bubowski)*

The fire started in the apartment on the ground floor. It started in the kitchen because a bag with dirt was left on the stove. Investigators deduce that the bag was ignited by heat from the pilot light [30]. The fire spread and damaged the living room and the kitchen. The other spaces in the apartment (bedroom, bathroom, office, …) were separated from the fire with a closed door. Afterwards, the damage to the remaining rooms was very limited. This leads to the conclusion that the volume of the fire (and the resultant backdraft) was rather small. Due to a lack of oxygen, the fire started to self-extinguish. Because of the insulation of the apartment, the heat was kept inside. The rise in temperature results in a continuous release of pyrolysis gases in the apartment. The volume was filled with unburned pyrolyzates.

When the fire department arrived on scene they don't notice any signs of a fire. It seemed a very routine operation. Initial operations consisted of installing the first hoseline and performing vertical ventilation of the staircase by opening the scuttle. Two three-man crews were sent into the building to perform search and rescue. One crew checked the apartment on the ground floor for victims while the second crew checked the floor above. Both crews took a hoseline inside. When the door to the apartment on the ground floor was opened, air rushed in and warm smoke was pushed out. This is followed by a flaming combustion that filled the complete staircase [31]. In the street, an amateur camcorder operator was making a video of the event. His film showed that the blowtorch of the backdraft lasted for 6.5 minutes.

The crew that opened the door on the ground floor made its way out but the crew that was working on the floor above is trapped. Three firefighters died because of this tragedy. FDNY asked NIST to model the fire in order to have a better understanding of what happened.

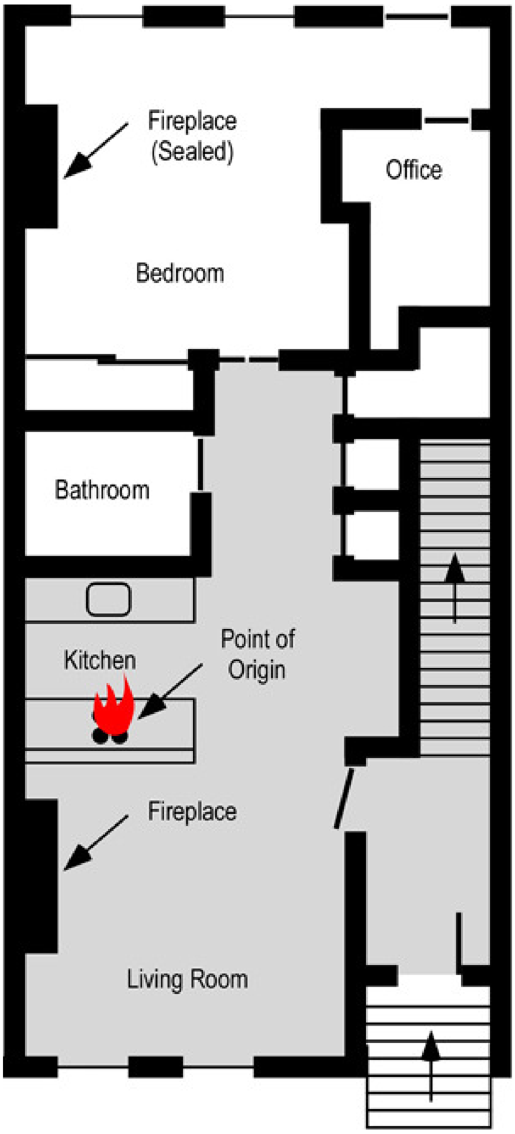

Figure 25 The lay-out of the fire apartment *(Picture: Ed Hartin)*

The NIST investigators used the zone model CFAST to model the fire. They modeled three volumes: a single room in the apartment that represents the living room and the kitchen (See Figure 25), the hallway and the duct of the fireplace in the living room. Research showed that the duct of the fireplace was the only source of fresh air (oxygen) during the fire. Fresh air is added to the fire until the smoke layer descends below the opening of the duct. During the remainder of the fire, the duct was used to evacuate smoke.

The model showed that the fire consumed the oxygen in the apartment. Oxygen levels drop below 10% after 15 minutes but pyrolysis continued. The unburned fuel accumulated in the apartment. When the opening of the door was simulated, warm air flowed out of the upper part of the door, followed by flaming combustion. The accumulated fuel in the apartment was sufficient to feed the flames in the staircase for a seven minute long blowtorch. These findings were very consistent with the testimonies of the firefighters on scene and the videotape that was made by the bystander.

The temperatures in the simulation showed that the temperature in the apartment rose to 300°C but decreased after the fire became ventilation controlled (See Figure 26). When the combustion stopped due to a lack of oxygen, no more energy was released into the volume. At the same time, energy was lost through the walls. When the door was opened, oxygen became available to the fire. The temperature of the flames exiting the doorway and filling the apartment were in the order of magnitude of 1200 °C. The three firefighters in the staircase didn’t have a chance.

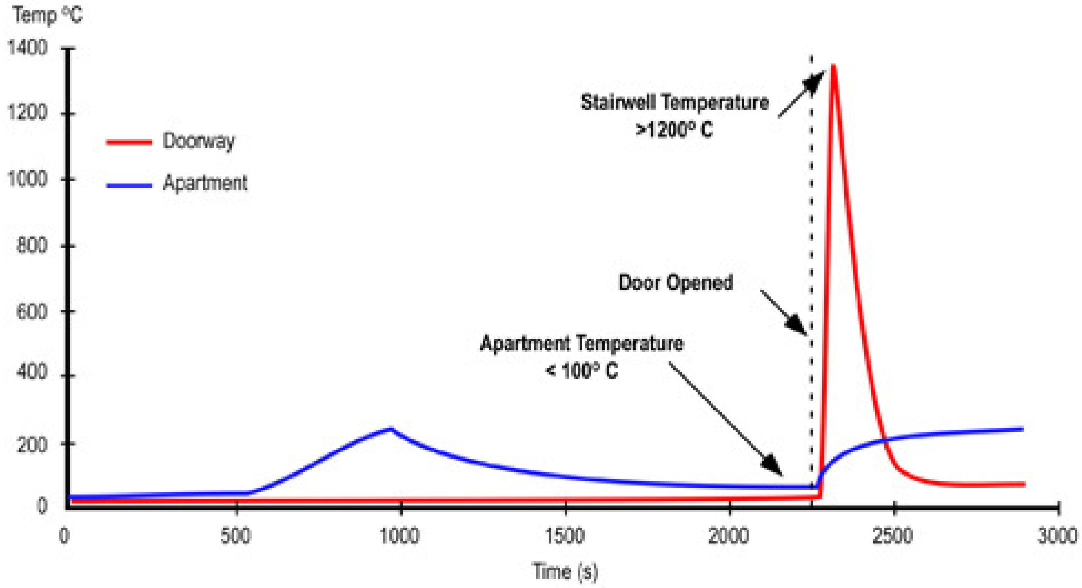

Figure 26 The temperature evolution in the apartment (blue) and in the doorway/staircase (red). *(Graphic: Ed Hartin & Richard Bukowski)*

3.3.3 Smoke explosion in Belgium: the Ukkel fire

August 30th 2008, units of the Brussels fire department were dispatched to a fire in Ukkel, one of the Brussels municipalities. When the first units arrived on scene, they faced a fully developed fire in a building of an abandoned complex that consisted of two buildings separated by a courtyard. The building (building A) measured 14 by 40 m. Since the building had been abandoned for years, the plants and trees in the courtyard have grown a lot. The bushes inside the courtyard had caught fire and threatened the second building of the complex. The second building (building B) was slightly larger and measured 14 by 45 m [32] (See Figure 29).

Figure 27 The slope of the terrain was quite impressive. Besides the slope, the large quantities of smoke block the view on the composition of the buildings. In the lower left corner of the picture one can see the ladder truck disappearing in the smoke. *(Picture: Robert Decock)*

It is clear that the resources needed to fight this fire go beyond the capacities of the first arriving engine. When the reinforcements arrived, the decision was taken to protect the second building. When the battalion chief completed his size-up, he noticed that no smoke had entered in building B yet. He decided to deploy two crews to fight the fire in the courtyard starting from building B. The wall separating building B from the courtyard consisted mainly of windows. All these windows had been broken by vandals, so it was an ideal position to attack the fire and protect building B. In order to fight the fire a 70 mm line and a 45 mm line were positioned.

During the intervention, the fire service was confronted with several major problems. Due to the geography of the terrain, it was impossible to perform a complete size-up. This effect is reinforced by the large quantities of smoke that the fire produced (See Figure 27). The distances to the nearest water hydrants were 150 and 250 m. This led to a situation where the firefighters needed more time to perform their tasks in an environment that has several hidden aspects.

Figure 28 View on building C with building B to the right and what is left of the bush between buildings A and B. Notice the engine on the right side of the picture. Due to the slope of the terrain, the road is two floors lower than in front of the building at that point. *(Picture: Robert Decock)*

At a certain point in time, a smoke explosion occurred in building B. The roof of the building was partially lifted and collapsed afterwards. At the time of the event, seven firefighters were in building B. Five managed to escape but two of them were trapped and died in the line of duty.

This fire and its tragic outcome have not been analyzed as was the case with a similar tragedy in The Netherlands [33] and the US [34]. Therefore the following explanation is only a theory that uses the information of the responders and the report to describe what had happened during the fire.
One piece of vital information that the firefighters on scene didn't have, was the existence of a third building, Building C. This building connected buildings A and B. Firefighters on the ground couldn't see this building due to the bushfire in the courtyard and the enormous quantities of smoke that were released by the fire (See Figure 27). A second piece of vital information was that the buildings had a slightly inclined roof. The void space under the roof of building B was approximately 500 m³. Seeing as the terrain was on a big slope, it was not possible for the firefighters to see that there actually was such an inclined roof and they all assumed that the buildings had a flat roof.

Figure 29 The smoke from building A (up) was going through the void attic space of building C (middle) towards building B (down). *(Picture: MSB from [35])*

The buildings probably had a connecting void space in the roof. Smoke produced at building A was accumulating in the void spaces of buildings C and B. When the mixture of air and smoke reached the lower flammability limit, the mixture became flammable. Seeing as the roof was lifted due to the shock wave, the mixture must have been close to ideal.

At a certain point the mixture must have been ignited in the voids space of building C. Probably the fire in building A supplied the ignition source. A pressure wave passed through the void spaces, followed by a flame front. The crew on scene could not have predicted that this would happen.

4 Ideas for further research

As can be seen in the reference list below, a large amount of (scientific) research has been done so far. Though there are still some topics that received very little attention. Below, a couple of suggestions for further research are given.

No backdraft research has been done yet with realistic fuel loads. This would be an interesting research topic. If the realistic fuel load behaves differently, then the fire service would like to know that.

The ignition source for backdraft is still not well understood. It remains unclear what type of source is capable of igniting a backdraft. More research into this item would enhance our understanding of the phenomenon.

The nature of buildings is changing. The level of insulation and "air tightness" are increasing. This has an influence on the fire behavior. Is there an influence on the occurrence of backdraft as well?

In paragraph 2.2.1 backdraft and ventilation induced flashover were described as "limit states" and the grey area between both was discussed. It would be interesting to know what are the factors that determine which behavior the fire will show?

5 References

[1] *Bolliger I (1995) Full Residential-Scale backdraft, Fire Engineering Research Report 95/1, University of Canterbury, New Zealand*

[2] *Karlsson B, Quintere J (1999) Enclosure fire dynamics, CRC Press*

[3] *Chitty R (1994) A survey of backdraught, Fire Research and development group, Fire research reports and memoranda, publication 5/94, UK*

[4] *Hartin E, Fire development and fire behavior indicators, CFBT-US*

[5] *Lambert K, Baaij S (2001) Brandverloop: technisch bekeken, tactisch toegepast, Sdu uitgevers (in Dutch or in French)*

[6] *Gojkovic D (2000) Initial backdraft experiments. Report 3121, Department of fire safety engineering, Lund university, Sweden*

[7] *Gottuk et al. (1999) The development and mitigation of backdraft: a real-scale shipboard study, Fire safety journal, Vol 33, p 261-282*

[8] *Hartin E (2010) Recent extreme fire behavior, www.cfbt-us.com/wordpress/?p=1046*

[9] *Fleischman CM, Pagni PJ, Williamson RB (1993) Exploratory backdraft experiments, Fire technology, Vol 29, p 298-316*
[10] *Tuomisaari M (1997) Smoke ventilation in operational firefighting, VTT publications 326, Technical research centre of Finland*
[11] *Aiping C et al (2011) Theoretical analysis and experimental study on critical conditions of backdraft, Journal of loss prevention in the process industry, Vol 24, p 632-637*
[12] *Fleischman CM, Pagni PJ, Williamson RB (1994) Quantitative backdraft experiments, proceedings on the fourth international symposium on fire safety science, June 13-17 1994, Ottawa, Canada, p 337-348*
[13] *Drysdale D (1998) An introduction to fire dynamics (2nd edition), John Wiley & Sons*
[14] *Fleischmann CM (1993) Backdraft phenomena, doctoral thesis, University of California, Berkley*
[15] *Fleischman CM, Pagni PJ, Williamson RB (1994) Salt water modeling of fire compartment gravity currents, proceedings on the fourth international symposium on fire safety science, June 13-17 1994, Ottawa, Canada, p 253-264*
[16] *Pérez-Jiménez et al. (2009) Influence of obstacles on the development of gravity current prior to backdraft, Fire technology, Vol 45, p 323-340*
[17] *Mao et al (2011) A model experimental study on backdraught in tunnel fires, Fire safety journal, Vol 46, p 164-177*
[18] *Weng WG, Fan WC (2003) Critical condition of backdraft in compartment fires: a reduced-scale experimental study, Journal of loss prevention in the process industries, Vol 16, p 19-26*
[19] *Horvat et al (2007) Numerical and experimental investigation of backdraft, Combustion science and technology, Vol 180, p 45-63*
[20] *Hartin E (2009) Gas explosions: Part 2, www.cfbt-us.com/wordpress/?p=430*
[21] *Madrzykowski D, Kerber S (2009) Evaluating firefighting tactics under wind driven conditions, NIST*
[22] *Madrzykowski D, Kerber S (2010) Wind-Driven Fire Research: Hazards and Tactics, NIST*
[23] *Weng WG, Fan WC (2002) Experimental study on the mitigation of backdraft in compartment fires with water mist, Journal of fire sciences, Vol 20, p 259-278*
[24] *Backdraft Harison NJ, retrieved from www.youtube.com/watch?v=B5wvCvmXnLs on October 4, 2013*
[25] *Croft WM (1980) Fires involving explosions: a literature review, Fire safety journal Vol 3, p 3-24*
[26] *La direction de la défence et la sécurité civile, sous-directions des sapeurs-pompiers (2003) Guide national de référence « explosions de fumées – embrasement généralisé éclair »*
[27] *Hartin E (2013) Smoke is fuel: recognizing the hazard, www.cfbt-us.com/wordpress/?p=1850*
[28] *Lambert K (2013) Rapid Fire Progress: een overzicht, De brandweerman, editie maart '13 (in Dutch)*
[29] *Bubowski R (1995) Modelling a backdraft: the fire at 62 watts street, NFPA Journal Vol. 89, p 85-89*
[30] *Hartin E (2009) 15 years ago: Backdraft at 62 Watts Street, www.cfbt-us.com/wordpress/?p=337*
[31] *Hartin E (2009) 62 Watts Street: Modelling the backdraft, www.cfbt-us.com/wordpress/?p=361*

[32] *Brandweer Brussel (2009) Interventie nr. 9146 van 30/08/2008 – hulp bij de technische debriefing (in Dutch and French)*

[33] *Helsloot I, Oomes E, Weever R (2009) Eindrapport evaluatie van de brand in De Punt op 9 mei 2008 (in Dutch)*

[34] *NIOSH firefighter fatality investigation and prevention program, www.cdc.gov/niosh/fire/*

[35] *MSB, 90 sekunder educational video for fire and rescue, Two firefighters die in a complex industrial fire*

[36] *Grimwood P, Hartin E, McDonough J, Raffel S (2005) 3D Firefighting, Training, Techniques & Tactics*

[37] *Hartin E (2013) UL vertical ventilation study: tactical implications, www.cfbt-us.com/wordpress/?p=1901*

[38] *Onderzoeksraad voor de veiligheid (2009) Brand in De Punt, translation: Fire in De Punt, movie evaluating a triple LODD in The Netherlands, (in Dutch)*

[39] *Guigay G et al. (2009) The use of CFD calculations to evaluate fire-fighting tactics in a possible backdraft situation, Fire technology, Vol 45, p 287-311*

[40] *CCS-Cobra training program (2010), Boras, Sweden*

[41] *Svensson S (2000) Fire Ventilation, Swedish Rescue Services Agency, Karlstad, Sweden*

[42] *Garcia K, Kauffmann R, Schelbe R (2006) Positive pressure attack for ventilation & firefighting, Pennwell, US*